A STUDY ON THE HEAT TRANSFER AND ENERGY PERFORMANCE IMPLICATIONS OF COOL ROOFS

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Tianyao Zhang

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A STUDY ON THE HEAT TRANSFER AND ENERGY PERFORMANCE IMPLICATIONS OF COOL ROOFS

Approved by:

Dr. Jason Brown, Advisor
School of Architecture
Georgia Institute of Technology

Dr. Godfried Augenbroe
School of Architecture
Georgia Institute of Technology

Dr. John Haymaker
School of Architecture and Building Construction
Georgia Institute of Technology

Date Approved: November 2013

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SUMMARY

In this study, we examined the effect of cool roofs on commercial and residential buildings in each climate zone, by looking at monitored case studies and DOE-2 simulations from various sources of literature; and using an online tool - the Cool Roof Calculator and a simple COP ratio model to validate the results of the case studies. The Cool Roof Calculator is based on a Simplified Transient Analysis of Roofs model that Wilkes (Wilkes, 1989) developed and validated to predict heat flows and temperatures within low-slope roof systems having known thermal properties.

It was found that the Cool Roof Calculator does not take building form into account, hence a sensitivity analysis was first conducted to rank the importance of various building parameters against one another. The analysis was conducted on the EPC normative model, which is a quasi-steady state model that approximates energy flows in a building based on a simplified description of the building and ignoring dynamic effects (Kim, Augenbroe, & Suh, 2013). The Latin Hypercube Sampling (LHS) technique was used for data sampling, and a multiple linear regression analysis was carried out to achieve the results. Results indicated that roof absorptance coefficient, aspect ratio and number of floors were the three parameters that either ranked highest or were important parameters, and were chosen for further parametric analysis to evaluate the impact of these building parameters on total building loads.

A simple COP ratio model was also developed to validate the results from the literature review and Cool Roof Calculator, and it was found that in terms of cost, for a prototype medium-sized commercial building, it is always beneficial to use a white roof, but cities in northern climates may have little advantage, and insulation may be a better choice.

CHAPTER 1

INTRODUCTION

1.1 Energy savings potential from the implementation of cool roofs

The rapidly growing building energy use has raised concerns globally. The contribution from buildings towards total national energy consumption, both residential and commercial, has steadily increased and reached figures as high as 40% in developed countries, and has exceeded the other major sectors such as industrial and transportation. With the growing population, day-by-day increasing demand for building services and comfort levels, along with the rise in time spent inside buildings, energy demand in buildings will surely stick to the upward trend in the future. For this reason, energy efficiency in buildings is one of the prime objectives in design and retrofit at regional, national, and international levels. The use of thermal insulation and special types of building materials has increased significantly in both hot and cold climates. Roofing systems with potential energy savings can help reduce the energy requirements for operating buildings, thereby reducing operating costs. In order to enhance the roof's contribution to energy consumption reduction, "green" roofing systems have been introduced, and have evolved into one of two categories: highly reflective or "cool" roof systems, and vegetative roof systems. This thesis mainly focuses on the benefits and implications of cool roof systems.

The heating and cooling loads of a building structure is determined by many factors, including the thermal characteristics of its envelope, its operation schedule, what it is used for, etc. It is proven that the radiative thermal properties of the roof of buildings have a great effect on annual energy consumption. The heat gain through a roof can be a significant component of the total cooling load from the envelope of a building, especially single-story buildings like elementary schools and residential houses. Roof cooling loads are maximized when little or no insulation is present and the exterior surface is dark in color, that is, when the roof albedo, or roof solar reflectance, is low. Albedo is the fraction of the incident solar energy which is reflected by the surface in question, it is the hemispherical reflectivity integrated over the solar spectrum. The solar reflectance of a roof's surface affects roof temperature, air temperature above the roof, and the heating and cooling energy use in buildings (H. Akbari & Konopacki, 1998). Lighter colored roofing membranes, including those covered with high albedo, low-absorptance, white coating materials, reflect incident solar energy, enabling them to stay cooler in the sun than low-albedo roofing materials (Hashem Akbari, Berhe, et al., 2005), since solar radiation is reflected rather than absorbed, thus achieving lower surface temperature and decreases the heat penetration into the building. Berdahl et al. (Berdahl & Bretz, 1997) has also demonstrated that there is a strong correlation between solar reflectance and surface temperature in sunlight through outdoor measurements. In general, the higher the reflectance and the emissivity of a roof coating, the cooler it stays. The emissivity, or thermal emittance, is the ratio of the radiant heat flux emitted by a sample to that emitted by a blackbody radiator at the same temperature. The solar radiation that is not reflected is absorbed, and this absorbed solar energy, now expressed by the roof surface temperature increase, is partially reemitted in the infrared spectrum. The infrared emittance of the surface gives the fraction of the maximum possible infrared radiation that the surface reemits. To maximize cooling energy savings, roof coatings should have high solar reflectance and high infrared emissivity, and maintain these properties for the service life of the coating. Surface temperature measurements indicated that a reflective or "cool" coating can reduce a white concrete tile's surface temperature under hot summer conditions by 4℃ and during the night by 2℃ (Synnefa, Santamouris, & Livada, 2006). Such "cool" roofs greatly promote energy efficiency, especially for buildings in cooling dominated climates.

1.2 Definition of cool roofs

Cool roofs are defined as a product with solar reflectivity of at least 0.70 and infrared emissivity of at least 0.75 by the Cool Roof Rating Council, or CRRC. Solar reflectance is determined by testing in accordance with ASTM C 1549 or E 903, using spectrophotometric measurements with an integrating sphere to determine the reflectance at each different wavelength. The average reflectance is then determined by an averaging process, using a standard solar spectrum. Thermal emittance is determined by testing in accordance with ASTM C 1371 or ASTM E 408.

Solar reflectance is the most important characteristic of a roof product in terms of yielding the highest energy savings during warmer months. An improvement in solar reflectivity from 0.80 to 0.90 can halve the absorbed solar radiation, while an improvement from 0.80 to 0.90 of infrared thermal emittance increases the thermal radiation by only 11%. Therefore, solar reflectivity ranks higher in importance than infrared thermal emittance in choosing a cool roof. Available roof products show a small range in infrared emittance but a large range in solar reflectivity.

1.3 Current cool roof provisions

It is difficult for building owners to assess the influence of roof properties on the lifetime cost of heating and cooling energy, which depends on various factors such as climate, the service life of the roof, and the time value of money (Hashem Akbari, Akbari, & Levinson, 2008). Building owners may also be unaware of the societal benefits of cool roofs, such as lower peak-power demand that could reduce the likelihood of power failures on hot days, and lower outdoor air temperatures that improve comfort and reduce the urban heat island effect. Hence, without cool roof standards, owners will tend to choose roofs that have the minimum initial construction cost, rather than the aggregate cost of construction and lifetime energy consumption. Therefore, ASHRAE and California Title 24 building energy-efficiency standards have included cool roof provisions. Cool roofs have been prescribed in the standard non-residential building in the 2005 California Energy Efficiency Standards for Residential and Nonresidential Buildings (Title 24). The code requires the heat gain of any compliant building not to exceed that of a building that has a cool roof.

1.4 The heating penalty of cool roofs

Although the application of cool roofs can significantly reduce cooling energy, a heating penalty, however, is sometimes sustained when high-albedo roofing material is applied, as less sunlight is absorbed by the roof during the heating season. In northernmost climates and cloudy climates, the increase in heating loads can sometimes offset the decrease in cooling loads, such as Madison and Seattle (Taha, Sailor, & Akbari, 1992). In the hot climate of Phoenix, on the other hand, the decrease in cooling loads can be much larger than the corresponding increase in heating loads, resulting in a net decrease in total annual energy need (Taha et al., 1992). That being said, in many locations and buildings however, the savings in cooling electricity dollars far exceed the penalties in heating gas dollars. In northern climates such as Minneapolis, the amount of snow covering the roof in the wintertime serves as an additional layer of insulation, and the cool roof is not exposed, thereby mitigating the heating penalty effect.

1.5 Objectives

The objective of this thesis is to determine under what kind of circumstances a cool roof should be applied; what climate zone, building form, or building use would benefit from a cool roof system. It is to be decided whether the heating penalty can outweigh the cooling energy savings and result in negative net saving, especially in northern climates where there is a large heating need.

Methodology in determining whether a cool roof is applicable in all climate zones and building conditions includes a literature review of papers on case studies of the benefits and penalties of implementing a cool roof system, a calculation in the ORNL-developed web-based Cool Roof Calculator, a sensitivity analysis/regression analysis in ModelCenter and Matlab, and parametric studies in Matlab. A simple COP ratio model is also developed to validate the results.

CHAPTER 2

LITERATURE REVIEW

2.1 Climate zones

Many field experiments have been carried out to demonstrate the effectiveness of cool roofs in reducing cooling-energy use in buildings. The chosen locations were mostly in the southern part of the county, as cooling-dominated climates would benefit the most from a light-colored roof. The climate zones referred to in this thesis are the U.S. Building America climate regions based on the climate designations used by the International Energy Conservation Code (IECC) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The IECC climate zone map was developed by Department of Energy researchers at Pacific Northwest National Laboratory (Briggs, Taylor, & Lucas, 2003). The map divided the United States into eight temperature-oriented climate zones, as shown in Figure 1. These zones are further divided into three moisture-oriented moisture regimes designated A (moist), B (dry), and C (marine). Climate zone boundaries follow county boundary lines. The climate region definitions are based on heating degree days, average temperatures, and precipitation.

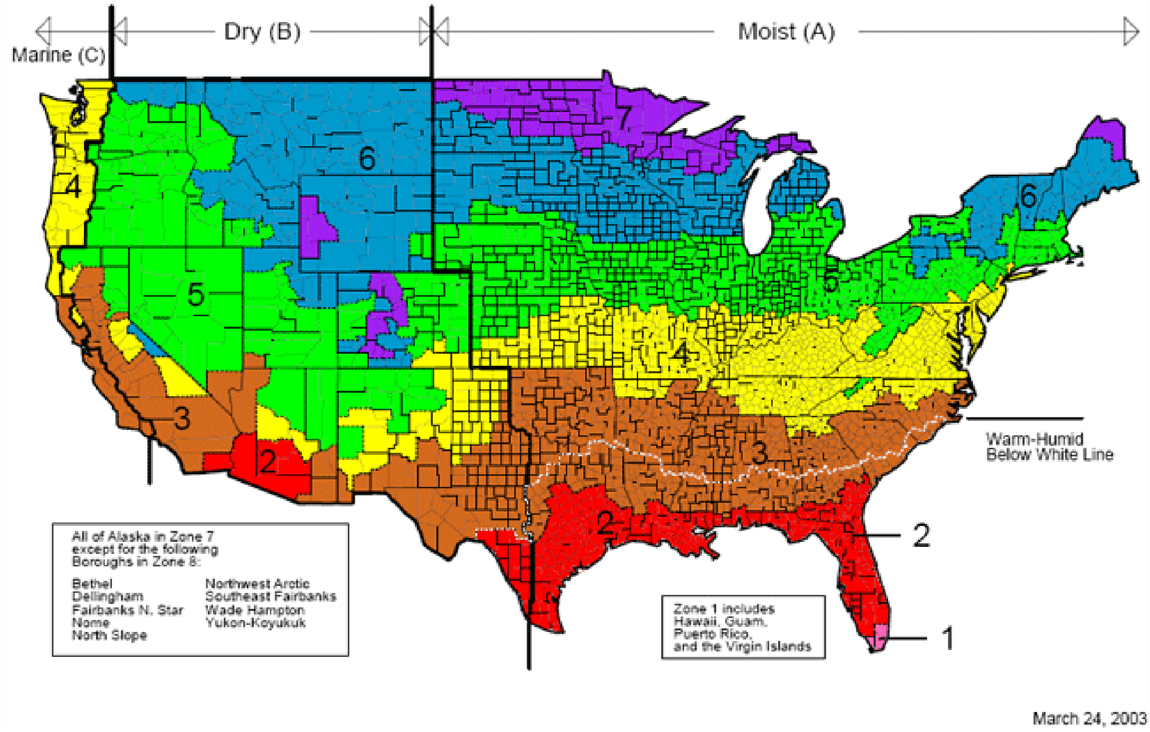


Figure 1 International Energy Conservation Code (IECC) climate regions (Briggs et al., 2003).

For reporting purposes, researchers at Department of Energy's (DOE) National Renewable Energy Laboratory further simplified the IECC map and combined the eight climate zones into five climate categories: Hot-humid, hot-dry/mixed dry, mixed-humid, marine, cold/very cold, and subarctic, as shown in Figure 2 (Baechler et al., 2010). The relationship between Building America and IECC climate zones is outlined in Figure 3.

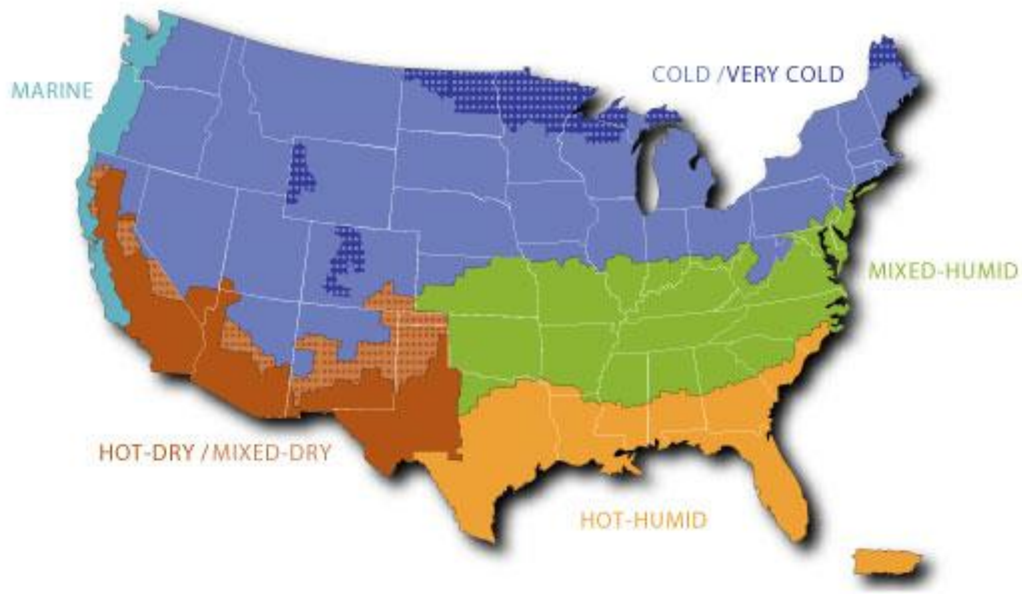


Figure 2 US climate zones recognized by Building America (Baechler et al., 2010).

Building America	IECC
Subarctic	Zone 8
Very Cold	Zone 7
Cold	Zones 5 and 6
Mixed-Humid	4A and 3A counties above warm-humid line
Mixed-Dry	Zone 4B
Hot-Humid	2A and 3A counties below warm-humid line
Hot-Dry	Zone 3B
Marine	All counties with a "C" moisture regime

Figure 3 Relationship between the Building America and IECC climate zones (Baechler et al., 2010).

2.2 Monitored case studies

Most of the literature on “cool roofs” are case studies done in spot locations, either monitoring existing buildings or simulating prototype buildings to examine the benefits of installing a cool roof system, that is, the reduction in cooling energy and net savings in dollars over the year.

Many full building experiments in Florida and California have examined the impact of reflective roof coatings on air conditioning energy use in a series of tests on occupied buildings. Parker et al. (Parker & Barkaszi Jr, 1997) have monitored nine single story residential houses in Miami (climate zone 1A), Cocoa Beach (climate zone 2A), and Tampa (climate zone 2A), Florida, respectively, before and after installation of high-albedo coatings to their roofs (roof albedo increased from 0.22 to 0.73), both with and without ceiling insulation scenarios, and received the results of a 2-43% reduction in air-conditioning energy use, with an average savings of 19%. Utility coincident peak electrical demand reduction between 5 and 6 p.m. varied from 12-38%, with an average of 22%. One important finding from this study was that larger energy savings were associated with no or poor ceiling insulation, or buildings with excessive attic air infiltration due to air handler return air leakage. This could lead to the conclusion that reflective coatings may be particularly appropriate for existing Florida residences in which the roof structure makes it difficult to retrofit insulation. One key issue remaining for development of the technology at that time was the influence on surface solar reflectance degradation, that is, the weathering and aging of reflective coating.

Several years later, Parker et al. (Parker, Sonne, & Sherwin, 2002) instrumented six side-by-side single story homes in Fort Myers, Florida (climate zone 1A), with identical floor plans and orientation, R-19 ceiling insulation, but with different roofing systems designed to reduce attic heat gain. Measurements showed that the three white reflective roofs (an increase in roof albedo from 0.08 to 0.77) would reduce cooling energy consumption by 18-26% and peak demand by 28-35%. The terra cotta tile roofs and white shingles would produce cooling savings of 3-9% and 3-5% respectively, while the sealed attic construction with an insulated roof deck would produce reductions of 6-11%. These results were consistent with the results of their previous research done in 1997, indicating that white reflective roofs yielded a greater savings in cooling energy consumption than purely sealed attics and insulated roof decks. Therefore, the conclusion from these two case studies were that residences in Florida, or climate zones 1 and 2, would benefit greatly from a white reflective roof, especially houses that have poor ceiling insulation. This piece of information would be extremely helpful when dealing with retrofits for single family housing units.

Akbari et al. (Hashem Akbari, Bretz, Kurn, & Hanford, 1997) conducted field experiments to monitor and measure the cooling energy consumption for one single story house and two single story school bungalows in Sacramento, CA (climate zone 3C). Cooling energy savings reached up to 63% from increasing the roof albedo from 0.18 to 0.79 for the R-11 insulated house, and 46% from increasing the roof albedo from 0.34 to 0.79 for the R-19 insulated school bungalows. Peak cooling demand was reduced by 25% and 20%, respectively, for the house and school bungalows. Later on, Akbari et al. (Hashem Akbari, Levinson, & Rainer, 2005) monitored the effects of cool roofs on energy use in six California buildings at three different sites: a retail store in Sacramento (climate zone 3C), and elementary school in San Marcos (climate zone 3C), and a four-building cold storage facility in Reedley (climate zone 3B). The estimated savings in average air conditioning energy use was about 52%, 17-18%, and 3-4%, respectively. Savings in peak demand during peak hours was about $10W/m^2$, $5W/m^2$, and $5\text{-}6W/m^2$, respectively. It was concluded that two factors contribute to the high savings in retail store buildings in CA: low roof/attic insulation and long hours of air conditioner operation. In comparison, the energy savings in the school building and the cold storage facility are about half of that of the retail store, which may due to shorter operation hours. Peak demand savings were significant even with R-29 roof insulation on the cold storage facility. This study also indicated that in monitoring energy use in occupied buildings, one needs to be careful since statistical variation exits due to occupancy behavior. For the retail store, data analysis was fairly straightforward since the operation of the HVAC systems were fairly uniform, but for the school building, the operation hours and its HVAC systems were haphazard mainly because of changes in classroom occupancy and frequent classroom door openings. This uncontrolled operation makes data analysis complicated and increases its tendency to errors, and unfortunately this applies to all monitored building energy use.

Konopacki et al. (Konopacki, Gartland, Akbari, & Rainer, 1998) measured summer daily cooling energy savings per unit roof area of 18, 13 and 2%, respectively for three California non-residential buildings – two medical offices in Davis and Gilroy and a retail store in San Jose. Assuming an aged solar reflectance of 0.55, estimated annualized cooling energy savings were 16%, 11% and 2% respectively, while peak-power demand reductions per unit roof area were 12%, 8% and 9%, respectively. This study indicated that since most roofs have regular maintenance schedules or need to be re-roofed or re-coated periodically, the change of the albedo could be done then by applying a reflective coating or covered with a new light-colored material, hence the cost would be limited to the incremental cost associated with the high-albedo material.

Konopacki et al. (Konopacki & Akbari, 2001) estimated cooling energy savings of 11% and a peak-power demand reduction of 14% in a large retail store in Austin, Texas (climate zone 2A). Estimated annual cooling energy savings can reach up to 6.8kWh/m^2, assuming an aged solar reflectance of 0.55. This study indicated that the type of buildings that could achieve the largest savings were those that have a tight plenum, low to moderate level of roof insulation, low efficiency air-conditioning equipment, long operating hours and large conditioned roof area. Akridge J.M. (J.M., 1998) also demonstrated the benefits of reflective roof surfaces on an educational center near Atlanta, GA (climate zone 3A), reporting a cooling energy use reduction of 21.6% on hot summer days.

More buildings were monitored for actual cooling-energy use data throughout cities around the world. Simpson et al. (Simpson & McPherson, 1997) measured reductions of up to 5% in total and peak air-conditioning load for two identical white (SR = 0.75) compared to gray (SR=0.30) and silver (SR=0.50) roofed scale model buildings in Tucson, Arizona (climate zone 2B). Overall on a 24-hour basis, increased roof albedo was found to be about as effective as addition of ceiling insulation in reducing building heat gain.

Kolokotroni et al. (Kolokotroni, Gowreesunker, & Giridharan, 2011) examined the impact of the application of a reflective paint on a flat roof in a naturally ventilated office building in the area of London, UK, where the climate is moderate with high heating demands. The results indicate that in the case of temperate climates, the type, operation and thermal characteristics of the building should be considered carefully to determine potential benefits of the application of cool roof technology. For the examined case study, it was found that a roof reflectivity of 0.6-0.7 was the optimum value to achieve energy savings in a cooled office. Bozonnet et al. (Bozonnet, Doya, & Allard, 2011) have shown that even for a moderate climate like Poitiers, central part of France, the cool roof of a typical low-rise public housing building decreases the mean outside surface temperature by more than 10℃, with low differences for lower temperatures, but a strong impact on the highest temperatures. Therefore, for typical buildings in France without any cooling active systems, the cool roof coating is an optimal passive solution to reduce cooling-energy use.

Akbari et al. (Taha et al., 1992) summarized the following percentage changes in heating and cooling loads resulting from an increased albedo. The results indicate that increase in heating energy offsets the decrease in cooling energy in terms of cost in the heating-dominated, or cool and cloudy climates of Madison (climate zone 5A) and Seattle (climate zone 4C), as shown in Table 1.

Table 1 Percent decrease and increase in loads resulting from increasing roof albedo from 0.3 to 0.7 (Taha et al., 1992)

Title	**High albedo materials for reducing building cooling energy use**
Author, Year	Haider Taha et al., 1992

Altering Roof Albedo	0.30 to 0.70			
Cooling Load Reduction	24.8%	37.6%	19.4%	12.1%
Heating Load Penalty	-5.2%	-7.7%	-7.7%	-35.6%
Annual Net Savings ($/m2)	-1.2%	-2.7%	1.7%	10.8%
Building Prototype	Residential, Houses			
Climate Zones	5A	4C	4A	2B
Location	Madison, WI	Seattle, WA	Washington DC	Phoenix, AZ

2.3 Computer simulations case studies

In addition to field studies, computer simulations of cooling energy savings from an increased roof albedo have been documented for buildings. Konopacki et al. (Konopacki, Akbari, Pomerantz, Gabersek, & Gartland, 1997) have presented an excellent summary of energy savings from applying a cool roof for both hot and cold regions in the US. Computational simulations using a DOE-2 program were conducted to estimate the net direct energy savings (cooling-energy savings minus heat-energy penalties) from reflective roofs on prototypical residential and commercial buildings in 11 representative U.S. metropolitan statistical areas (MSAs). The 11 prototypical buildings were specified as single-family residential (old and new), office (old and new), retail store (old and new), school (primary and secondary), health (hospital and nursing home), and grocery store. Most prototypes were simulated with two heating systems: gas furnace and heat pump. The numbers in the figures below are results from using gas furnaces for heating equipment. Metropolitan-wide savings were as much as $37M for hot and sunny climates like Phoenix (climate zone 2B) and $35M for marine areas like Los Angeles (climate zone 3C) and as low as $3M in the heating-dominated climate of Philadelphia (climate zone 4A). A detailed summary of the DOE simulation results is outlined in Table 2 and Table 3. Negative numbers indicate that they are penalties rather than actual savings. Figure 4 through 7 illustrate the net cooling energy savings, electricity savings, heating penalties and peak cooling demand savings for the 11 metropolitan areas.

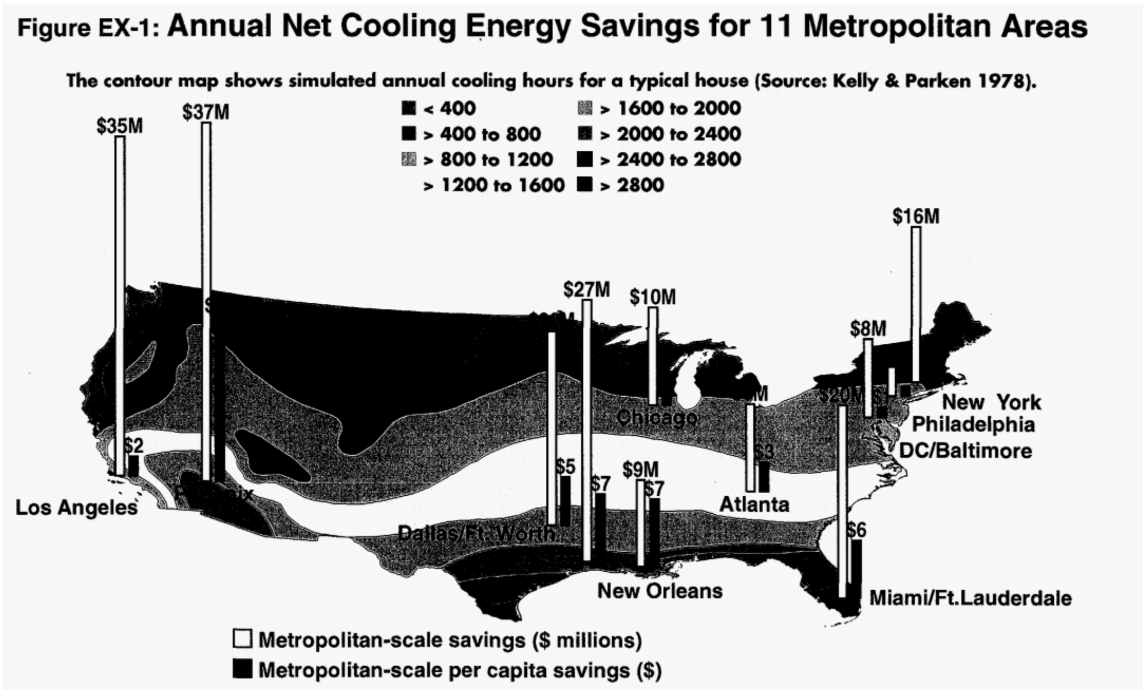


Figure 4 Annual Net Cooling Energy Savings in Dollars (Konopacki et al., 1997)

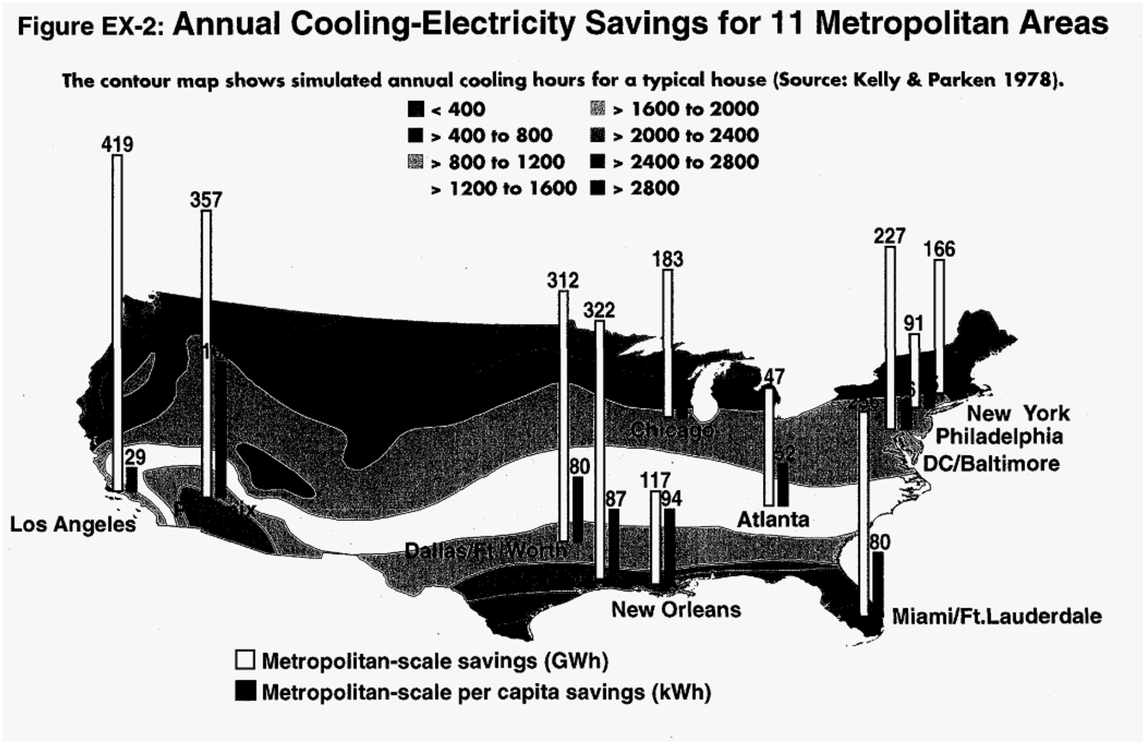


Figure 5 Annual Cooling Electricity Savings (Konopacki et al., 1997)

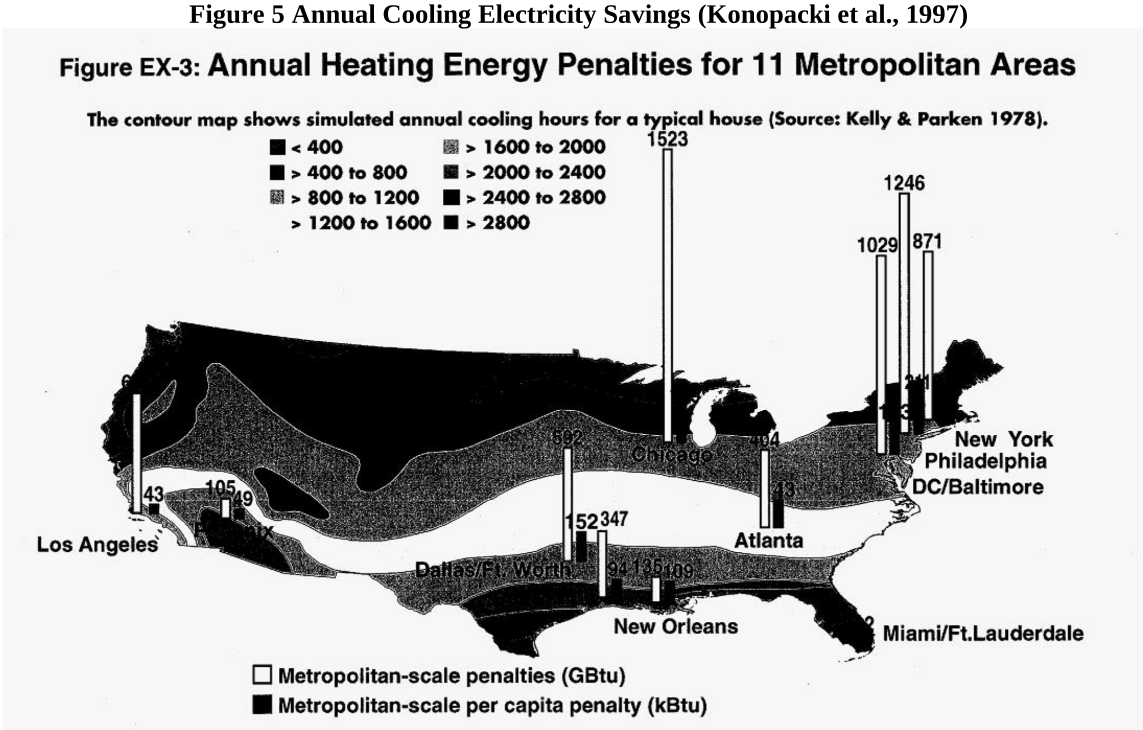


Figure 6 Annual Heating Energy Penalties (Konopacki et al., 1997)

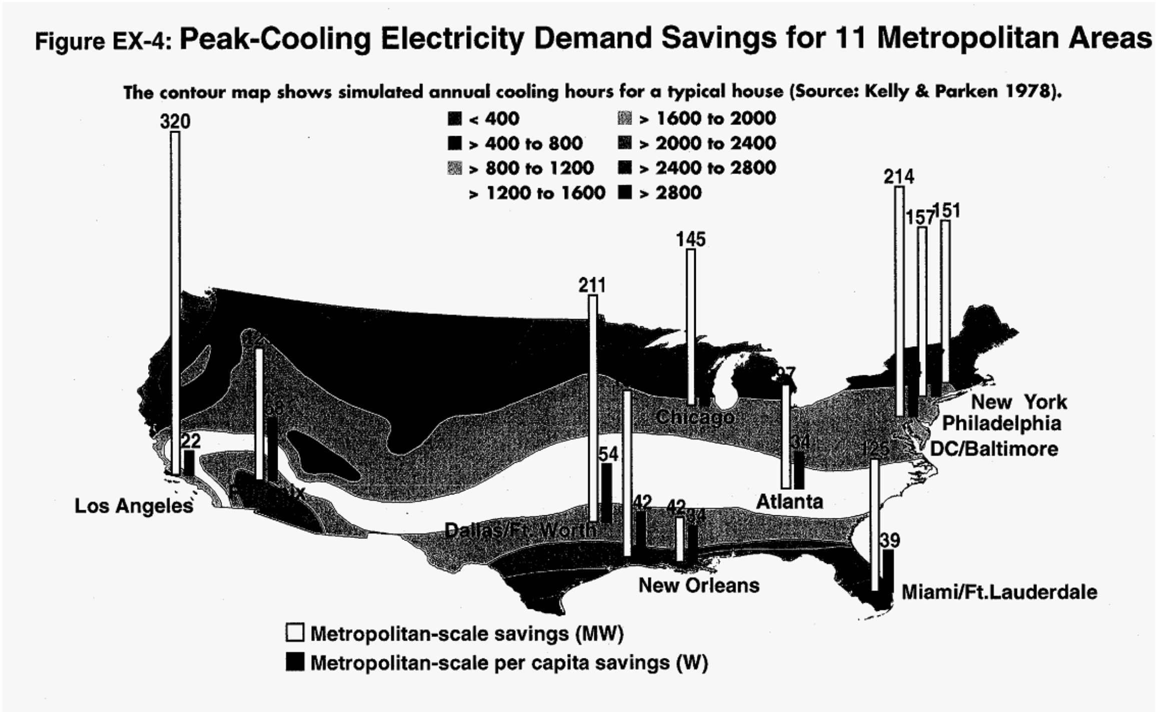


Figure 7 Peak-Cooling Electricity Demand Savings (Konopacki et al., 1997)

Table 2 Summary of Konopacki et al.'s simulation study for residential houses

Title	Author	Roof Insulation after Retrofit	Altering Roof Albedo	Methodology	Cooling Energy Consumption Savings	Peak Cooling Demand Savings	Heating Energy Consumption Savings	Annual Net Savings ($/m2)	No. of Buildings	Building Prototype	Climate Zones	Location
Cooling energy saving potentials of light-colored roofs for residential and commercial buildings in 11 U.S. metropolitan areas	S. Konopacki et al., 1997	R-19 roof insulation	0.25 to 0.55	DOE-2 Simulation	9%	6%	-2%	4%	11	Single Story Residential Houses	3A	Atlanta, GA
					8%	4%	-2%	1%			5A	Chicago, IL
					15%	9%	-5%	9%			3C	Los Angeles, CA
					6%	5%	-2%	3%			2B	Dallas, TX
					8%	6%	-3%	6%			2A	Houston, TX
					6%	5%	0	5%			1A	Miami, FL
					10%	6%	-4%	7%			2A	New Orleans, LA
					7%	6%	-1%	1%			4A	New York City, NY
					10%	10%	-2%	-1%			4A	Philadelphia, PA
					7%	4%	-2%	6%			2B	Phoenix, AZ
					8%	5%	-2%	1%			4A	Washington DC

Table 3 Summary of Konopacki et al.'s simulation study for commercial offices

Title	Author	Roof Insulation after Retrofit	Altering Roof Albedo	Methodology	Cooling Energy Consumption Savings	Peak Cooling Demand Savings	Heating Energy Consumption Savings	Annual Net Savings ($/m2)	No. of Buildings monitored	Building Prototype	Specific Building Type	Climate Zones	Location
Cooling energy saving potentials of light-colored roofs for residential and commercial buildings in 11 U.S. metropolitan areas	S. Konopacki et al., 1997	R-19 roof insulation	0.25 to 0.70	DOE-2 Simulation	5%	4%	-7%	4%	11	Commercial	Single Story Offices	3A	Atlanta, GA
					4%	4%	-4%	1%				5A	Chicago, IL
					7%	6%	-37%	7%				3C	Los Angeles, CA
					3%	3%	-9%	3%				2B	Dallas, TX
					4%	4%	-10%	4%				2A	Houston, TX
					4%	2%	0%	4%				1A	Miami, FL
					5%	5%	-12%	5%				2A	New Orleans, LA
					4%	2%	-3%	2%				4A	New York City, NY
					6%	6%	-4%	2%				4A	Philadelphia, PA
					5%	2%	-29%	5%				2B	Phoenix, AZ
					4%	4%	-6%	2%				4A	Washington DC

As we can see from Table 2 and Table 3 above, for single story residential houses the heating penalty may outweigh the cooling savings in northernmost climates such as Philadelphia, but for single story commercial buildings, offices in particular, there is a net savings in dollars in all of the climate zones studied, as the heating penalty exists but does not outweigh the summertime cooling savings. This may be because the internal gain of commercial buildings is larger compared to residential housing units.

Hashem et al. (Hashem Akbari & Konopacki, 2004) reported that simulations in a DOE-2 model indicated that the cooling-energy use can be reduced by about 20% for low-rise residential and commercial buildings in Toronto, Canada by increasing the albedo of roofs by 0.2 (from moderate-dark to medium-light color).

Akbari (Hashem Akbari et al., 1997) conducted simulations of the three aforementioned Sacramento commercial buildings with the DOE-2.1E building energy program to confirm the measured data. It should be noted that the climate data that was input in the model was the actual real data gathered at the sites, rather than using typical meteorological year data. However large discrepancies were found between simulated and measured results, as shown in Figure 8. It was found that simulations significantly underestimate savings and cooling load reductions. Due to insufficient information the author was unable to explain the reason thoroughly and only provided two possible explanations: the failure of the program to simulate the cooling energy use of the modeled building, or the author's failure to accurately describe the building through model input. The large discrepancies exist between measured and simulated savings for the buildings, even though the modeling of albedo modifications is simple. The discrepancy is most unexpected at Site B, since the school buildings are essentially simple one-room structures that are supposedly easy to model with DOE-2.

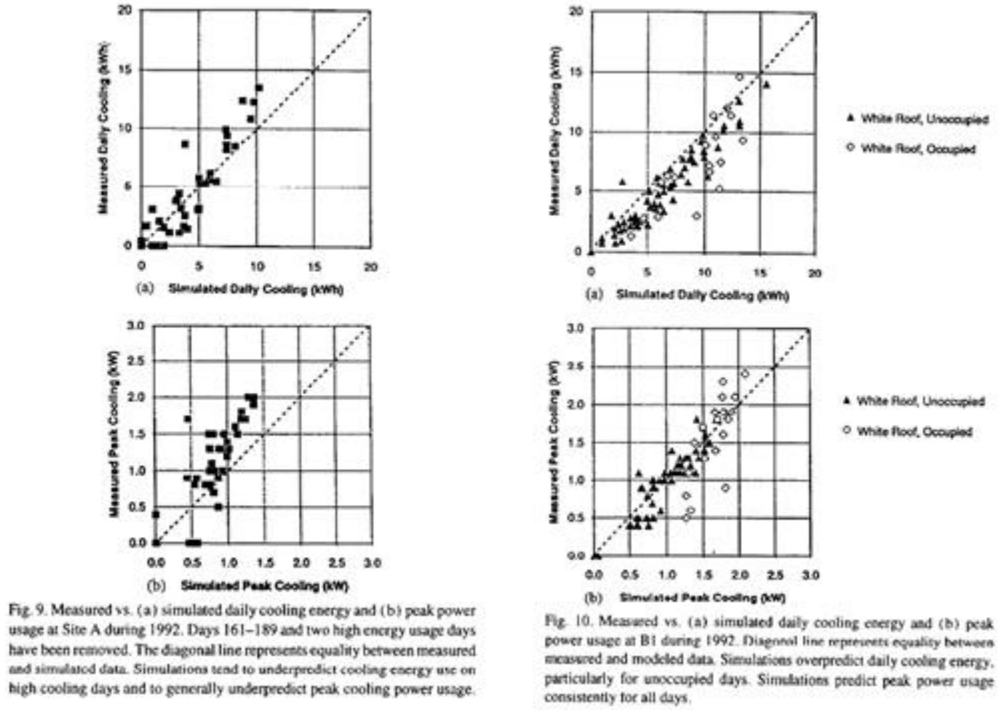


Figure 8 Comparison of measured and simulated data (Hashem Akbari et al., 1997)

Parker et al. (Parker et al., 1998) performed simulations in a DOE-2.1E model to validate the measured results on 11 homes in Florida as well, and found that with modified functions included in the model to account for attic duct heat gains, heat transfer in the attic due to radiation, attic ventilation, ceiling framing, and the increasing conductivity of insulation with increasing temperature, the simulation model correlated well with the measured data (illustrated in Figure 9), as it predicts the peak attic air temperatures reasonably well, produces meaningful although perhaps conservative estimates for changes to roof solar reflectance, and tracks the major influence observed from the Florida field studies – percentage savings from reflective surfaces are higher with low ceiling insulation levels and flat roof geometries. When taken overall, the DOE-2 model predicted an average of 18.6% summer cooling energy savings for the 11 described cases in Central and South Florida against a measured savings of 19.3%. Although short of the measured average reduction of 7.7 kWh/day, the relative accuracy of the simulation gives confidence that the revised model will produce meaningful results. It should be noted though, that the model predicts a somewhat higher temperature than measured for the white roofs which should result in conservative estimates, which is the same conclusion that Akbari (Hashem Akbari et al., 1997) had drawn in their studies. Figure 9 below demonstrates the results:

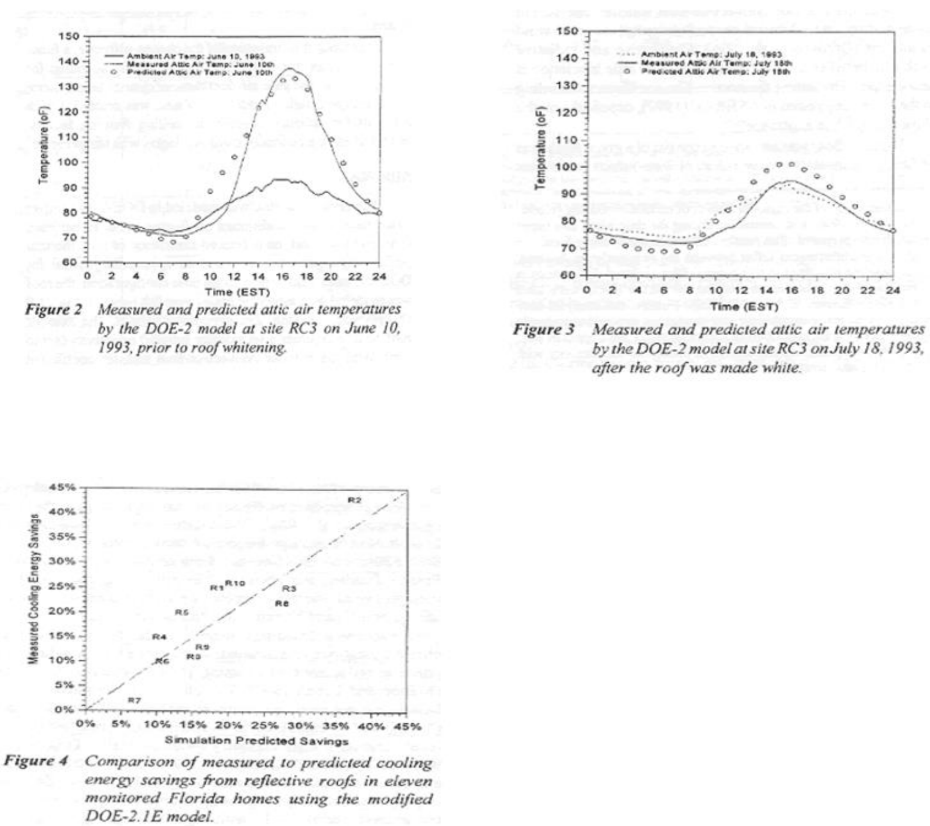


Figure 9 Comparison of measured and simulated data (Parker et al., 1998)

With the confidence from the successful simulation on the impact of reflective roofing systems, Parker et al.'s research was expanded beyond the state lines of Florida. To address the variations of climate in the U.S., a total of 14 climate locations, 11 residential houses were simulated. Results indicate that except in the northernmost locations (Minneapolis and Detroit), and the cool and cloudy locations (Seattle and San Francisco), the combined cost of heating and cooling was shown to be lower for reflective roof surfaces than conventional ones. The advantage of light colored roof surfaces is greatest in the lower latitudes, generally below 37 degrees north latitude. In climates where it is heating-dominated, particularly above 40 degrees north latitude, there was little advantage to be gained from reflective roofing and in the coldest locations, adding insulation was clearly a better choice. The savings decrease as the climate gets cooler, but for most building types, net savings are positive in colder climates as far north as Chicago. Table 4 compares the benefits of a cool roof and additional roof insulation in the 14 cities.

Table 4 Ordinal cost comparison for installing a new reflective coating compared to adding insulation among 14 different cities (Parker et al., 1998)

Los Angeles	*
Atlanta	+
Houston	+
Ft. Worth	+
Miami	+
Fresno	+
Phoenix	+
Detroit	-
New York	-
San Francisco	-
St. Louis	-
Minneapolis	-
Seattle	-
Denver	-

- *: For new construction, annual energy cost is less with a new reflective roof than adding an additional increment of R-11 insulation.
- +: As above, also a lower cost even for a weathered roof rather than adding R-11 insulation.
- -: It is more cost effective to add an additional layer of roof insulation.

Table 5 Summary of case study 3

Title	Author	Roof Insulation after Retrofit	Altering Roof Albedo	Cooling Energy Consumption Savings	Heating Energy Consumption Savings	Annual Net Savings ($/m2)	No. of Buildings monitored	Building Prototype	Building Description	Climate Zones	Location
Measured and simulated performance of reflective roofing systems in residential buildings	Parker et al., 1998	R-38 Ceiling	0.10 to 0.75	17%	-3%	-0.01	11	Residential Homes	Single story, 140 m^2 floor area	5A	Detroit, MI
		R-38 Ceiling		16%	-4%	0.01				4A	New York City, NY
		R-25 Ceiling		39%	-4%	0.06				3C	Los Angeles, CA
		R-30 Ceiling		22%	-5%	0.23				3A	Atlanta, GA
		R-30 Ceiling		15%	-4%	0.31				2A	Houston, TX
		R-30 Ceiling		16%	-4%	0.3				2B	Fort Worth, TX
		R-30 Ceiling		17%	-4%	-0.01				3C	San Francisco, CA
		R-30 Ceiling		6%	-3%	0.07				4A	St. Louis, MO
		R-44 Ceiling		14%	-2%	0				6A	Minneapolis, MN
		R-19 Ceiling		14%	-8%	0.4				1A	Miami, FL
		R-38 Ceiling		16%	-4%	-0.01				4C	Seattle, WA
		R-30 Ceiling		21%	-5%	0.32				3A	Fresno, CA
		R-38 Ceiling		22%	-4%	0.03				5B	Denver, CO
		R-30 Ceiling		15%	-4%	0.47				2B	Phoenix, AZ

From Table 5 we can see that for single story residential houses, the heating penalty outweighs the cooling energy savings in climates that are either cold like Detroit and Minneapolis or cloudy like Seattle and San Francisco. As the heating and cooling load of residential houses are mainly shell-dominated, therefore a change in roof surface properties may lead to significant changes in loads and consumption. Figure 10 illustrates the influence of new reflective roofs on residential buildings on annual heating energy, cooling energy and costs across the U.S. It is not surprising that in northernmost climates the net savings in cost drop to a very small advantage, or no advantage at all, for residential buildings.

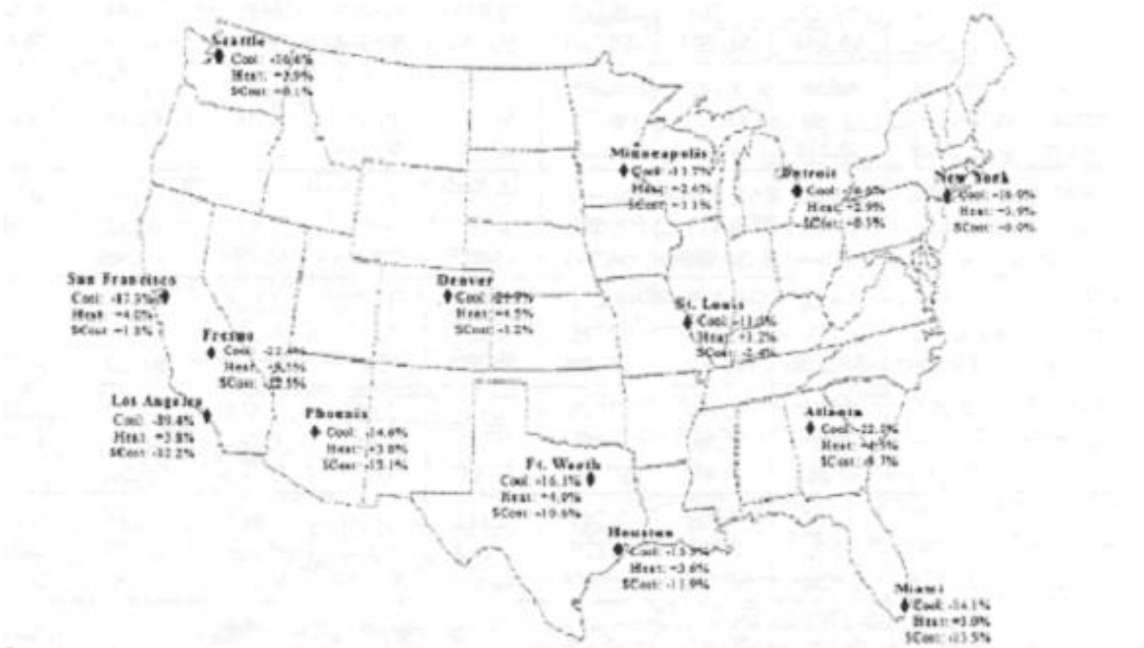


Figure 10 Influence of new reflective roof coatings on residential buildings on annual heating and cooling energy and costs around the U.S. (Parker et al., 1998)

Freund (Freund, Dettmers, & Reindl, 2006) simulated the overall energy consumption in a retail building with four roof insulation levels in two northern climate locations (Minneapolis, MN and Denver, CO) with reflective roofs (solar reflectance 65%) and with black roofs (solar reflectance 6%), respectively, in the simulation program

TRNSYS. TRNSYS was chosen because it allows more detailed and flexible building simulation than DOE-2. Results proved that the savings of cooling energy for buildings such as "a big retail box" outweighed the additional energy that would be required for space heating, in terms of costs. Snow cover was also shown to decrease the heating penalty of using reflective roofs.

Synnefa et al. (Synnefa, Santamouris, & Akbari, 2007) estimated the effect of using cool roof coatings on energy loads and thermal comfort in residential buildings in various climates, performing computational simulations in TRNSYS for residential buildings in 27 cities around the world that represented different climatic conditions, including Mediterranean, humid continental, subtropical arid, desert conditions, etc. between -33.46° and 43.4° latitude. For the base case the solar reflectance was considered to be 0.2, and for the improved cases due to the use of cool coatings the solar reflectance reached up to 0.85. The infrared emittance was considered to be 0.9. The study admitted to its limitations – that this specific building type may not necessarily be representative of the typical house in all of the tested locations, but the purpose of the study was to report the cooling energy savings and potential wintertime penalties from changing the roof's solar reflectance comparatively for various climatic conditions. Representative results included 5 different climate conditions: a) Abu Dhabi where there was no heating load, b) New Delhi where the cooling load is significantly larger than the heating load, c) Casablanca where the heating load is almost half compared with the cooling load, d) Damascus where cooling and heating loads were almost equal and e) Tokyo where heating is dominated.

The cooling load reduction and the heating load increase resulting from an increase in solar reflectance (from 0.2 to 0.85) for a U-value of 0.84 roof are shown in Figure 11. It is illustrated that the effect of an increased albedo roof has a more significant impact on cooling loads reduction than on heating loads increase for the 5 climates studied. Increasing the solar reflectance of the roof by 0.65 yields a cooling load reduction that ranges between 16.1-47.2 kWh/m^2 for the five cases, while the corresponding increase in heating loads ranges only between 0.4-16.2 kWh/m^2. This suggests that using a cool roof could also be beneficial for climates that have heating loads that are comparable to cooling loads. In order to estimate the energy use and savings however, the types of systems used for cooling and heating as well as the energy prices for the systems used should be taken into account.

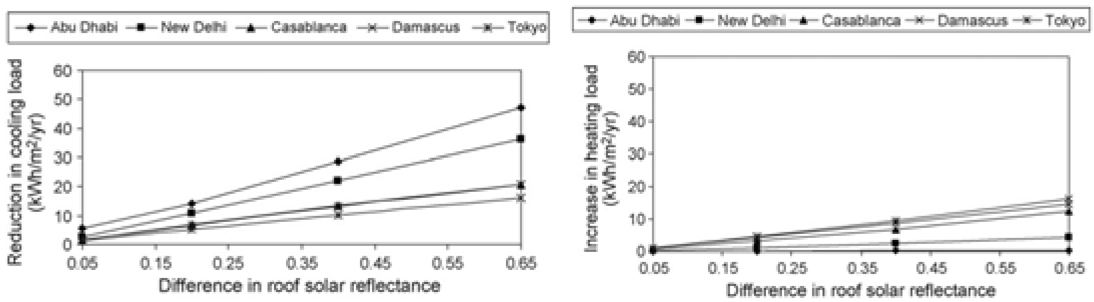


Figure 11 The impact of roof solar reflectance changes on cooling and heating loads for a roof U-value equal to 0.84 in different cities (Synnefa et al., 2007).

Figure 12 depicts the changes in cooling and heating loads resulting from an increase in roof solar reflectance of 0.65 for more cities. The figure indicates that potential savings are greater in cooling dominated climates; cooling loads were reduced by 18-93% and peak demand reduced by 11-27%. But for heating dominated areas like Mexico City, the winter penalty makes a cool roof not as beneficial. The reason that Mexico City has a high heating need while located at a relatively low latitude is because it has a high altitude of 2400 m. As temperature decreases about 6℃ per kilometer, the effect can be quite significant.

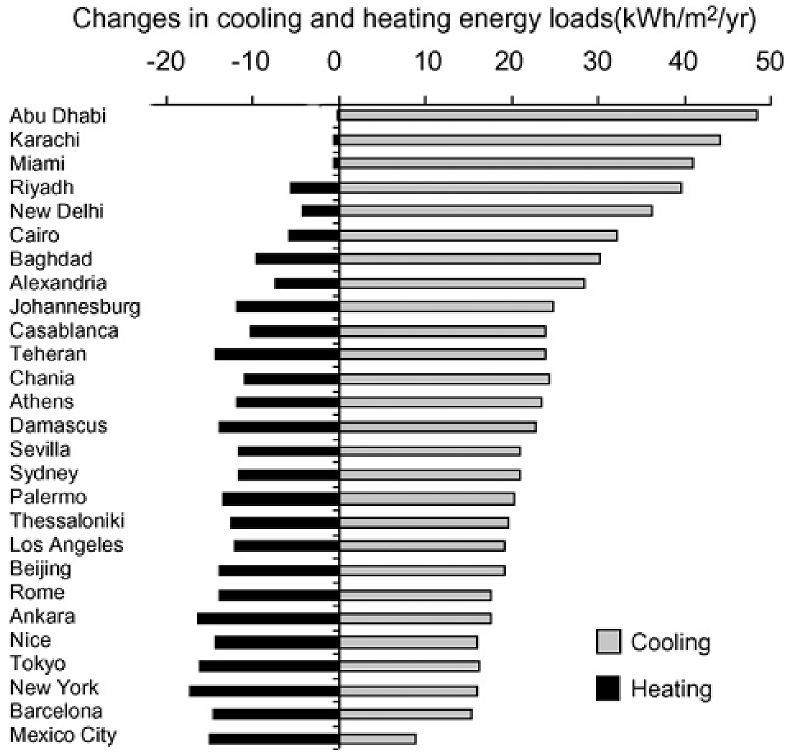


Figure 12 Changes in heating and cooling loads in various cities after applying cool roof coatings (Synnefa et al., 2007)

Shariah et al. (Shariah, Shalabi, Rousan, & Tashtoush, 1998) also used the simulation software TRNSYS to simulate the effect of exterior surface absorptivity on heating, cooling, and total energy loads in mild and hot climates in Jordan. Results demonstrate that the absorptivity of a flat roof has a large effect on heating and cooling loads while that of the side walls is almost negligible. Total loads were reduced considerably when light colors were used with further reductions resulting from an increase in roof insulation.

Many of the papers on case studies presented a quantitative cooling energy savings from cool roofs. These cooling energy savings varied from 2% to 80% and averaged about 20%. The literature indicated that the peak cooling energy savings from cool roofs lies between 8% and 35%, which depends on ceiling insulation levels, duct placement and attic configuration. Many others have performed field experiments or simulations in evaluating the impact of roof albedo on annual net energy use (Levins & Herron, 1990), (Hageman & Modera, 1996), (Petrie, Childs, & Christian, 1998). Percentages are summarized in Table 6 for these case studies. Some case studies do not provide complete information on building parameters, hence the blanks in the table below. One problem about the monitored case studies is that they don’t provide the actual heating penalty or annual net savings in costs for each city and building, therefore making it hard to compare with the simulated studies.

Table 6 Summary of monitored case studies

Title	Author, Year	Roof Insulation after Retrofit	Altering Roof Albedo	Cooling Energy Consumption Savings	Peak Cooling Demand Savings	No. of Buildings	Building Prototype	Building Description	Climate Zones	Location
Roof solar reflectance and cooling energy use: field research results from Florida	Parker et al., 1997	R-18	0.22 to 0.73	15%	16%	9	Residential, Houses	Single story, 167 m^2 floor area	1A	Miami, FL
		No ceiling insulation	0.22 to 0.73	43%	38%				2A	Cocoa Beach, Florida
		No ceiling insulation	0.22 to 0.73	25%	30%				2A	Tampa, FL
Comparative evaluation of the impact of roofing systems on residential cooling energy demand in Florida	Parker et al., 2002	R-19	0.08 to 0.77	18-26%	28-35%	6	Residential, Houses	Single story, 114.4 m^2 floor area	1A	Fort Myers, FL
Demonstration of cooling savings of light colored roof surfacing in Florida commercial buildings: Retail strip mall	Parker et al., 1997	R-11	0.29 to 0.75	25%	29%	7	Commercial, Retail	Single story retail stores	2A	Cocoa Beach, FL
Demonstration of cooling savings of light colored roof surfacing in Florida commercial buildings: Our Savior's School	Parker et al., 1996	R-19	0.23 to 0.68	10%	35%	1	Commercial, Elementary School	1000 m^2 floor area	2A	Cocoa Beach, FL
Peak power and cooling energy savings of high-albedo roofs	Akbari et al., 1997	R-11	0.18 to 0.79	63%	25%	1	Residential, Houses	Single story, 170 m^2 floor area	3C	Sacramento, CA
		R-19	0.34 to 0.79	46%	20%	2	Commercial, School Bungalows	Single story, 89 m^2 floor area	3C	Sacramento, CA

Table 6 continued

Monitoring the energy-use effects of cool roofs on California commercial buildings	Akbari et al., 2005	R-7	0.21 to 0.83	52%	10W/m2	1	Commercial, Retail	Single story, 1600 m^2 floor area	3C	Sacramento, CA
		R-30	0.25 to 0.79	17-18%	5W/m2	1	Commercial, School	Single story, 570 m^2 floor area	3C	San Marcos, CA
		R-29 insulation	0.04 to 0.65	3-4%	5-6W/m2	4	Commercial, Cold Storage Facility	Single story, 4900 m^2 floor area	3B	Reedley, CA
The effects of roof albedo modification on cooling loads of scale model residences in Tucson, Arizona	Simpson et al., 1997	R-30	0.30 to 0.75	5%	5%	4	Scale model buildings	-	2B	Tucson, AZ
		No ceiling insulation		18-28%	18-28%					
Measured Energy Savings and Demand Reduction from a Reflective Roof Membrane on a Large Retail Store in Austin	S. Konopacki et al., 2001	R-12	0.05 to 0.83	11%	14%	1	Commercial, Retail	10,000 m^2 floor area	2A	Austin, TX
Demonstration of energy savings of cool roofs	S. Konopacki et al., 1998	R-8	0.24 to 0.60	18%	-	1	Commercial, Medical Office	Single story 3,170m^2 floor area	3C	Davis, CA
		R-19	0.25 to 0.60	13%	-	1	Commercial, Medical Office	Single story 2,380 m^2 floor area	3C	Gilroy, CA
		With radiation barrier	0.16 to 0.60	2%	-	1	Commercial, Retail	Single story 3,290 m^2 floor area	3C	San Jose, CA
High-Albedo Roof Coatings-Impact on Energy Consumption	Akridge, J.M., 1998	-	-	9-28%	-	1	Commercial, Educational Center	-	3A	Atlanta, GA
Radiant Barrier Field Tests in Army Family Housing Units at Fort Benning, Georgia	Levins & Herron, 1990	-	-	3-17%	-	-	Residential, Houses	-	3A	Fort Benning, GA

Table 6 continued

Radiation Control Coatings on Rough Surfaced Roofs at a Federal Facility: Two Summers of Monitoring Plus Roof and Whole Building Modeling	Petrie et al., 1998	moderately well-insulated	0.09 to 0.53	7%	-	1	Commercial, Federal Facility	-	3A	Tallahassee, FL
Energy Savings and HVAC Capacity Implications of a Low-Emissivity Interior Surface for Roof Sheathing	Hageman & Modera, 1996	R-38	-	16%	-	1	Residential, Houses	-	2A	Austin, TX

From the simulation studies and monitored case studies we have come to the following conclusions:

- The DOE-2.1 simulation program tends to underestimate the cooling energy savings.
- For residential houses, except in the northernmost locations such as Minneapolis, Philadelphia and Detroit, and the cool and cloudy locations such as Seattle and San Francisco, the combined cost of heating and cooling was shown to be lower for reflective roof surfaces than conventional ones.
- For commercial buildings, results from DOE-2 simulations indicated that it is always cost-beneficial to install a cool roof, no matter which climate zone.
- For residential houses, in climates particularly above 40 degrees north latitude, there was little advantage to be gained from a reflective roofing system, and adding insulation was a better choice.
- Prototypes with gas heating systems had annual electricity and net dollar savings greater than those with electric heat pumps, because of the higher cost of electric heat relative to gas.
- The lower the roof insulation, the relatively greater the cooling energy savings.
- Prototypes with longer hours of operation showed relatively larger savings with respect to those with shortened schedules.
- The relative cooling savings in summertime were most significant in residential prototypes because their cooling loads were shell dominated; the others were internal load dominated.
- Buildings with tight plenum, low to moderate level of roof insulation, low efficiency air-conditioning equipment, long operating hours and large conditioned roof area would most likely benefit from a reflective roof.
- For uninsulated buildings, although the cooling savings in summertime is greater than well-insulated buildings, but the heating penalty is also larger, hence system efficiency

and electricity and gas prices need to be considered to determine the net savings in dollars over a year.

However, many of these case studies do not provide enough information on their choice of input parameters, such as cooling equipment size and efficiency, or the type of heating system (gas furnace or electric heat pump), and does not provide statistics in reductions in loads as opposed to consumption, therefore making it hard to make comparisons.

2.4 Weathering of cool roof coatings

The case studies above have demonstrated that cooling energy savings of 10% to 70% can be achieved by applying high-albedo coatings to residential buildings in California and Florida, however the cool roof coatings tend to have a decrease in efficiency over time, because of surface accumulations and material degradation. Bretz et al. (Bretz & Akbari, 1997) examined some high-albedo coatings at various stages of exposure to determine the magnitude of this effect. Most of the albedo degradation of coatings occurred within the first year of application, and even within the first two months of exposure. After the first year, the degradation slowed, with data indicating small losses in albedo after the second year. Measured data was used to estimate the effects of weathering of white roofs on seasonal cooling energy savings, and an estimate of 20% reduction from first year energy savings for all subsequent years was concluded. Although washing the roofs with soap is effective at restoring original albedo, calculations show that it is not cost-effective to hire someone to clean a high-albedo roof only to achieve energy savings. Instead, it would be useful to develop and identify dirt-resistant high-albedo coatings.

Akbari et al. (Hashem Akbari, Berhe, et al., 2005) provided a detailed report on the aging and weathering of cool roofing membranes, which included 13 white roof material samples that had been exposed for 5-8 years in eight different locations, and found that their solar reflectivity had dropped from 0.8 to nearly 0.5. However it was also concluded from the study that washing the samples could almost completely restore the original reflectivity.

Levinson et al. (Levinson, Berdahl, Asefaw Berhe, & Akbari, 2005) also summarized that degraded solar reflectances range from 0.3 to 0.8, depending on exposure. Wiping removed much of the black carbon that significantly reduces the solar spectral reflectances of light-colored roof membranes, but was less effective at removing the organic carbon. Rinsing and/or washing removed nearly all of the remaining soil layer, though bleach was required to clear isolated dark spots of biomass.

2.5 Other topics on cool roofs

In recent years, roofing membranes offering high solar reflectance properties have become the most highly recommended or prescribed roofing materials among the industry and code agencies. While these roofing membranes are aesthetically pleasing and effective, Desjarlais et al. (A. Desjarlais, Petrie, Miller, Gillenwater, & Roodvoets, 2006) have conducted a study on evaluating the energy performance of ballasted roof systems, as it is well known that the mass of a ballasted roof can reduce peak roof temperatures and delay the heat flow into a building. An experimental study was initiated to quantify the energy savings of ballasted roofing systems and to compare their energy performance to that of "cool roof" membranes. In order to model the behavior of the ballasted and control systems, the Simplified Transient Analysis of Roofs (STAR) model that Wilkes (Wilkes, 1989) developed and validated to predict heat flows and temperatures within low-slope roof systems having known thermal properties such as thermal conductivities and specific heats. STAR is a transient one-dimensional finite difference model for heat conduction which can accommodate TMY2 weather files and use weather data that was measured along with the thermal performance of the test roofs in the project. The model simulates heat flow in multilayer roofing systems. Three years of continuous monitoring in East Tennessee generated data to compare the energy performance of six ballasted systems and a system with an exposed black membrane to that of a system with an exposed white membrane. Three systems had different stone ballast loadings and one had uncoated paver ballast. Both a black and a white single-ply membrane served as controls. Two additional paver ballasts, coated with highly reflective white coatings, were deployed a year into the project. Results indicated that the cooling loads for the heavy and medium stone-ballasted and uncoated paver-ballasted systems were approximately the same as for the white system; cooling loads for the light weight stone systems were slightly larger than for the white system but significantly less than for the black system; cooling loads for coated pavers with heavy and medium loading showed cooling loads significantly less than for the white system; only the cooling load of the white system showed significant effects of weathering, which was complete by the start of the second year of the project; heating loads for the ballasted systems showed random variation as loading increased and type changed. Except for the heavy weight stone system, they were about the same as for the white system; the heavy weight stone system showed slightly less heating load than the black system but this is considered an anomaly due to rain effects; all evidence on clear days of diurnal behavior showed the heavy weight stone and uncoated paver systems performing equally due to the same thermal mass despite different solar reflectance.

Al-Sanea (Al-Sanea, 2002) has conducted a study on the comparison and evaluation of the thermal characteristics of six variants of a typical roof structure used in building constructions in the Kingdom of Saudi Arabia, using a numerical model based on an implicit finite-volume method to calculate the time-dependent temperature variation in composite layers under nonlinear boundary conditions. The results indicated that the absorbed solar radiation was the dominant source of energy gain by the roof, and the contribution of the radiation exchange was more than twice that of the heat convection. The inclusion of a 5-cm thick molded polystyrene layer reduces the roof heat-transfer load to one-third of its value in an identical roof section without insulation. Using a polyurethane layer instead, reduces the load to less than one-quarter. A slightly better thermal performance is achieved by locating the insulation layer closer to the inside surface of the roof structure but this exposes the water proofing membrane layer to larger temperature fluctuations.

Kabre (Kabre, 2010) has aimed to find a scientific rating scheme for roof system for the warm humid tropics. Since overall air-to-air transmittance (U-value) or thermal resistance (R-value) of roofs are based on steady-state heat conduction and cannot provide a satisfactory performance criterion for rating roofs, a new thermal performance index was developed, based on thermal comfort and actual thermal performance of a roof design option. A mathematic modeling methodology is demonstrated locations in India and Cairns respectively, and a new thermal performance index (TPI*) is calculated for a number of roofs. This new index would indicate in percentage terms how much performance is achieved on a scale with the range of acceptable elevation and the worst elevation for a given roof in a particular climate. The results indicate that roofs with high thermal resistance are not necessarily always the best option. There are a few limitations of the thermal performance index (TPI*) however, it does not integrate other parameters such as change in ventilation rate, color, cloud cover, diffuse radiation etc., and it has not been applied to other climatic regimes and conditioned environment, nor has it been validated with field experimentation. It should be noted that the TPI metric is based on thermal comfort for occupants under the roof, rather than the level of energy use reduction, which differs from most of the scientific studies.

Desjarlais et al. (A. O. Desjarlais, Zaltash, Atchley, & Ennis, 2010) have aimed to quantify the thermal performance of various vegetative roofing systems relative to black and white roofs. Low-slope roof systems were constructed and instrumented for continuous monitoring in the mixed climate of East Tennessee. The study summarized the annual cooling and heating loads per unit area of three vegetative roofing systems with side-by-side comparison to black and white roofing systems as well as a test section with just the growing media without plants. Results indicated that vegetative roofs reduced cooling loads in the cooling dominated periods and heating loads in the heating dominated periods in the mixed climate of East Tennessee, compared to the white control system due to the thermal mass, extra insulation, and evapotranspiration associated with the vegetative roofing systems. Vegetative roofs also reduced the temperature and temperature fluctuations experienced by the membrane.

CHAPTER 3

COOL ROOF CALCULATOR

In order to achieve the generalization of thermal performance, U.S. Department of Energy's Oak Ridge National Laboratory has developed a Cool Roof Calculator that estimates cooling and heating savings for low-slope roofs with non-black surfaces, aiming to assist commercial building owners and/or operators in selection of a roof. It is essentially a one-dimensional, transient heat transfer model, driven by the ambient weather conditions. The calculator uses the STAR model, mentioned in the previous chapter, to predict temperatures and heat fluxes throughout roofs, generating annual heating loads and cooling loads per unit area of various low-slope roof configurations, using TMY2 typical meteorological year weather data (Wilkes, 1989). Locations in the drop-down menu within the calculator were selected to include climates that ranged from cooling-dominated to heating-dominated. The limitation of the Cool Roof Calculator is that it only considers the heat transfer process on a flat surface without considering the effects of the entire building envelope, i.e. opaque area and window area, or the building form, i.e. tall skinny buildings and low chubby buildings. It is not whole building model, therefore may not be accurate in numbers in a cardinal sense, but may still produce valid results in an ordinal sense.

For a commercial building, if the roof is given solar radiation control, the Cool Roof Calculator indicates the annual savings in operating costs to condition a building under the roof. Alternatively, the tool can give the amount of conventional thermal insulation without radiation control that a roof needs in order to have the same annual energy costs as the roof with the existing amount of conventional insulation and solar radiation control. (Petrie, Atchley, Childs, & Desjarlais, 2001). It does not however, address savings in peak demand due to radiation control. Generally, it showed the same dependence on changes in solar reflectance, infrared emittance and insulation level at typical locations including cooling-dominated, mixed climate and heating-dominated climates.

In order to compare the results of the CRC with the case studies in the literature review, the same cities and same building envelope parameters such as roof insulation levels, solar reflectance, etc. were selected in the calculator to generate the results. For some of the case studies, parameters were not specified, for those cases (mostly DOE simulations) the average parameters were chosen for the CRC calculation, listed in Table 7 below. Since most case studies had natural gas as energy source for heating, we chose to use the same energy source as well in the calculator.

For the base case (black roof), the assumptions were it had a solar reflectance of 0.05 and infrared emittance of 0.9.

Table 7 Average CRC parameters

Building Roof Parameters	Average Value from CRC
Roof Insulation Level	R-10
Solar Reflectance	0.50
Infrared Emittance	0.60
Summertime cost of electricity	$0.10/kWh
Wintertime cost	$0.70/therm
Air conditioner efficiency (COP)	2.0
Heating system efficiency	Boiler, 0.7

Table 8 Average daily solar load, Cooling Degree Days and Heating Degree Days of Selected Cities

Location	Climate Zone	Average Daily Solar [Btu/ft^2]	CDD_{65}	HDD_{65}
Miami, FL	1A	1556	4126	141
Tampa, FL	2A	1555	3311	697

Table 8 continued

Austin, TX	2A	1549	2965	1630
Houston, TX	2A	1405	2810	1552
Phoenix, AZ	2B	1839	3814	1154
Fort Worth, TX	2B	1559	2414	2304
Tucson, AZ	2B	1835	2762	1553
Atlanta, GA	3A	1477	1611	3089
Las Vegas	3B	1805	3066	2293
Sacramento, CA	3C	1557	1144	2793
San Francisco, CA	3C	1509	68	3238
New York City, NY	4A	1268	1001	5089
Philadelphia, PA	4A	1264	1053	5180
Seattle, WA	4C	1061	127	4867
Chicago, IL	5A	1243	748	6449
Madison, WI	5A	1247	520	7504
Detroit, MI	5A	1199	566	6728
Denver, CO	5B	1466	622	6012
Minneapolis, MN	6A	1257	634	8002
Duluth, MN	7	1173	140	10213
Fairbanks, AK	8	810	29	14170

CDD_{65}: Annual sum ÷24 of hourly differences between hourly air temperature and 65 °F when hourly air temperature is more than 65 °F. [Annual F-day]

HDD_{65}: Annual sum ÷24 of hourly differences between 65 °F and hourly air temperature when hourly air temperature is less than 65 °F. [Annual F-day]

Table 9 Comparison of results from monitored case studies and Cool Roof Calculator

Results from Monitored Case Studies								Results from Cool Roof Calculator			
Roof Insulation after Retrofit	Altering Roof Albedo	Cooling Energy Consumption Savings	Peak Cooling Demand Savings	Building Prototype	Building Description	Climate Zones	Location	Cool Roof Application	Annual Net Savings ($/m2)	Cooling Load Reductions	Heating Load Reductions
R-18	0.22 to 0.73	15%	16%	Residential Houses	Single story, 167 m^2 area	1A	Miami, FL	Yes	0.68	53%	-1%
No ceiling insulation	0.22 to 0.73	43%	38%			2A	Cocoa Beach, Florida	Yes	1.89	55%	-1%
No ceiling insulation	0.22 to 0.73	25%	30%			2A	Tampa, FL	Yes	2.06	54%	0%
R-11	0.29 to 0.75	25%	29%	Commercial Retail	Single story retail stores	2A	Cocoa Beach, FL	Yes	1	57%	-2%
R-19	0.23 to 0.68	10%	35%	Commercial School	1000 m^2 floor area	2A	Cocoa Beach, FL	Yes	0.46	51%	-1%
R-11	0.18 to 0.79	63%	25%	Residential Houses	Single story, 170 m^2 floor area	3C	Sacramento, CA	Yes	0.63	62%	-5%
R-19	0.34 to 0.79	46%	20%	Commercial School	Single story, 89 m^2 floor area	3C	Sacramento, CA	Yes	0.31	62%	-6%
R-7	0.21 to 0.80	52%	10W/m2	Commercial Retail	Single story, 1600 m^2 floor area	3C	Sacramento, CA	Yes	1.01	64%	-5%
R-30	0.25 to 0.79	17-18%	5W/m2	Commercial School	Single story, 570 m^2 floor area	3C	San Marcos, CA	Yes	0.21	63%	-5%
R-29 insulation	0.04 to 0.70	3-4%	5-6W/m2	Commercial Cold Storage Facility	Single story, 4900 m^2 floor area	3B	Reedley, CA	Yes	0.16	46%	-1%
R-30	0.30 to 0.75	5%	5%	Scale model buildings	-	2B	Tucson, AZ	Yes	0.4	58%	-5%
No ceiling insulation		18-28%	18-28%					Yes	2.07	56%	-2%

Table 9 continued

R-12	0.05 to 0.83	11%	14%	Commercial Retail	10,000 m^2 floor area	2A	Austin, TX	Yes	1.03	65%	-5%
R-8	0.24 to 0.60	18%	-	Commercial Medical Office	Single story 3,170m^2 floor area	3C	Davis, CA	Yes	0.68	43%	0%
R-19	0.25 to 0.60	13%	-	Commercial Medical Office	Single story 2,380 m^2 area	3C	Gilroy, CA	No	0	41%	-2%
With radiation barrier	0.16 to 0.60	2%	-	Commercial Retail	Single story 3,290 m^2 floor area	3C	San Jose, CA	Yes	0.05	31%	1%
-	-	9-28%	-	Commercial Educational Center		3A	Atlanta, GA	Yes	0.52	33%	2%
-	-	3-17%	-	Residential Houses		3A	Fort Benning, GA	Yes	0.6	33%	2%
moderately well-insulated	0.09 to 0.53	7%	-	Commercial Federal Facility		3A	Tallahassee, FL	Yes	0.69	36%	2%
R-38	-	16%	-	Residential Houses		2A	Austin, TX	Yes	0.2	34%	0%

Table 10 Comparison of results from DOE simulations and Cool Roof Calculator

Results from DOE Simulations									Results from Cool Roof Calculator			
Roof Insulation after Retrofit	Altering Roof Albedo	Cooling Energy Consumption Savings	Peak Cooling Demand Savings	Heating Energy Consumption Savings (penalty if negative)	Annual Net Savings ($/m2)	Building Prototype	Climate Zones	Location	Cool Roof Application	Annual Net Savings ($/m2)	Cooling load	Heating load
R-19	0.25 to 0.55	9%	6%	-2%	4%	Residential Houses	3A	Atlanta, GA	Yes	0.52	33%	2%
		8%	4%	-2%	1%		5A	Chicago, IL	Yes	0.23	32%	-2%
		15%	9%	-5%	9%		3C	Los Angeles, CA	Yes	0.23	32%	4%
		6%	5%	-2%	3%		2B	Dallas, TX	Yes	0.65	33%	2%
		8%	6%	-3%	6%		2A	Houston, TX	Yes	0.66	33%	3%
		6%	5%	0	5%		1A	Miami, FL	Yes	0.82	31%	5%
		10%	6%	-4%	7%		2A	New Orleans, LA	Yes	0.64	33%	3%
		7%	6%	-1%	1%		4A	New York City, NY	Yes	0.32	32%	0%
		10%	10%	-2%	-1%		4A	Philadelphia, PA	Yes	0.33	32%	-1%
		7%	4%	-2%	6%		2B	Phoenix, AZ	Yes	0.9	29%	4%
		8%	5%	-2%	1%		4A	Washington DC	Yes	0.36	32%	0%

Table 10 continued

	0.25 to 0.70	5%	4%	-7%	4%	Commercial Offices	3A	Atlanta, GA	Yes	0.52	33%	2%
		4%	4%	-4%	1%		5A	Chicago, IL	Yes	0.23	32%	-2%
		7%	6%	-37%	7%		3C	Los Angeles, CA	Yes	0.23	32%	4%
		3%	3%	-9%	3%		2B	Dallas, TX	Yes	0.65	33%	2%
		4%	4%	-10%	4%		2A	Houston, TX	Yes	0.66	33%	3%
		4%	2%	0%	4%		1A	Miami, FL	Yes	0.82	31%	5%
		5%	5%	-12%	5%		2A	New Orleans, LA	Yes	0.64	33%	3%
		4%	2%	-3%	2%		4A	New York City, NY	Yes	0.32	32%	0%
		6%	6%	-4%	2%		4A	Philadelphia, PA	Yes	0.33	32%	-1%
		5%	2%	-29%	5%		2B	Phoenix, AZ	Yes	0.9	29%	4%
		4%	4%	-6%	2%		4A	Washington DC	Yes	0.36	32%	0%
R-38	0.10 to 0.75	17%	-	-3%	-0.01	Residential Houses	5A	Detroit, MI	Yes	0.1	59%	-8%
R-38		16%	-	-4%	0.01		4A	New York City, NY	Yes	0.12	59%	-7%
R-25		39%	-	-4%	0.06		3C	Los Angeles, CA	Yes	0.14	58%	-3%

Table 10 continued

R-30	22%	-	-5%	0.23	3A	Atlanta, GA	Yes	0.27	60%	-6%
R-30	15%	-	-4%	0.31	2A	Houston, TX	Yes	0.37	59%	-5%
R-30	16%	-	-4%	0.3	2B	Fort Worth, TX	Yes	0.35	59%	-5%
R-30	17%	-	-4%	-0.01	3C	San Francisco, CA	No	-0.02	59%	-6%
R-30	6%	-	-3%	0.07	4A	St. Louis, MO	Yes	0.2	59%	-7%
R-44	14%	-	-2%	0	6A	Minneapolis, MN	No	0	59%	-10%
R-19	14%	-	-8%	0.4	1A	Miami, FL	Yes	0.67	55%	-2%
R-38	16%	-	-4%	-0.01	4C	Seattle, WA	No	-0.04	59%	-7%
R-30	21%	-	-5%	0.32	3A	Fresno, CA	Yes	0.32	60%	-5%
R-38	22%	-	-4%	0.03	5B	Denver, CO	Yes	0.06	59%	-8%
R-30	15%	-	-4%	0.47	2B	Phoenix, AZ	Yes	0.55	54%	-4%

Conclusions as follows:

- The Cool Roof Calculator tends to give large savings in cooling loads and small penalties in heating loads.
- The Cool Roof Calculator is not a whole building model, hence it does not take into account building characteristics, not only in terms of the envelope, i.e. distinguish between different building forms and shapes, but also regarding occupant behavior and operational patterns.
- In all 8 climate zones tested, only the cloudy climates of Seattle, Gilroy and San Francisco, cold climates of Minneapolis and Detroit yielded a negative savings over the year in terms of cost. For other cities, it seems that applying a cool roof would always be beneficial in terms of cost.
- The Cool Roof Calculator only provides detailed calculations for loads, but not for consumption, which makes it hard to make comparisons to the case studies discussed previously in terms of energy savings.

CHAPTER 4

SENSITIVITY ANALYSIS OF BUILDING SHAPE AND ENVELOPE PARAMETERS

The case studies in Chapter 2 and Cool Roof Calculator in Chapter 3 do not take building shape and form into account, as most case studies make the assumption that the building is a single story rectangular box. However, to answer whether a cool roof is applicable for a certain building shape and form, and from a design perspective in what design cases a cool roof should become a priority of the design team and in what situations it may be less of a priority, we need to evaluate building envelope parameters against one another in terms of the level of effect on heating and cooling loads. Since it is unfeasible to evaluate every single parameter regarding shape and form in building energy calculations, a sensitivity analysis is needed to help pick out the building parameters that rank either highest or is considered important in deciding the type of roofing system. Therefore, in order to evaluate the importance of building envelope parameters against one another, and also expand beyond the limitations of the Cool Roof Calculator and consider the effects of building shape and form, a sensitivity analysis was applied to a set of building parameters that may have significant impacts on heating and cooling loads. All 8 ASHRAE climate zones were studied, and 15 representative cities were chosen to represent each climate subtype, as listed in Table 11 below.

Table 11 Representative City for each Climate Zone Subtype

Climate Zone	City
1A	Miami
2A	Houston

Table 11 continued

2B	Phoenix
3A	Atlanta
3B	Las Vegas
3C	SF
4A	Philadelphia
4B	Albuquerque
4C	Seattle
5A	Chicago
5B	Denver
6A	Minneapolis
6B	Helena
7	Duluth
8	Fairbanks

Sensitivity analysis is the study of how the uncertainty in the output of a mathematic model or system can be apportioned to different sources of uncertainty in its inputs (Saltelli et al., 2008). Sensitivity may be measured by monitoring changes in the output, e.g. by linear regression. There are two main approaches to determine the sensitivity of input parameters to outputs of a building energy model: local sensitivity analysis and global sensitivity analysis. Local sensitivity analysis, also known as the One-at-a-time approach, is one of the simplest approaches in the sense that it moves one input variable at a time and keeps others at their baseline or nominal values, and then returning the variable to its nominal value, then repeating for each of the other inputs in the same way. Despite its simplicity however, this approach does not fully explore design space as it does not take into account the simultaneous variation of input variables, meaning that the One-at-a-time approach cannot detect the presence of interactions between input variables (Czitrom, 1999). On the contrary, a global sensitivity analysis is more effective in robustly estimating the importance of input variables over a wide range, usually across a group of buildings. Common techniques include parametric methods such as multiple linear regression analysis.

The DIVA function in Grasshopper, Rhino (Jakubiec & Reinhart, 2011) was first applied to a set of parameters to see how this tool works with sensitivity analyses. However after a few trials and errors it was found that DIVA cannot effectively conduct a parametric study, as combined with the Octopus function it is essentially an optimization process – finding input combinations to achieve a minimum or maximum value for the objective, while the goal we are trying to achieve is explore design space over a large range and examine trends of numerous design variables. Moreover, as DIVA integrates EnergyPlus, it is not very efficient when dealing with a large pool of variables and scenarios, as the calculation time for EnergyPlus can be long, and the process may not be efficient when we have numerous building models. More importantly, the IDF file for EnergyPlus gets written over every time a new scenario is generated, therefore making it unfeasible to vary the roof albedo for each scenario.

Since DIVA cannot conduct a thorough parameter sweep, other options were considered. Due to the large scale of design space in this study, the global sensitivity analysis is applied and multiple linear regression analysis is used to rank the importance of parameters.

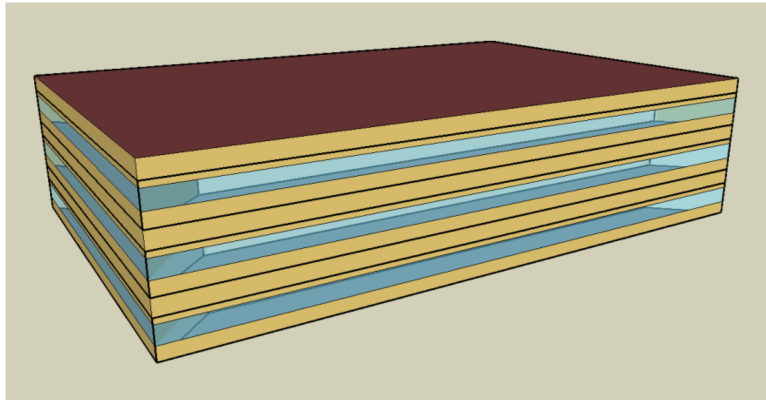
In view of the above limitations, it was decided to perform the sensitivity analysis with a tailored approach based with a reduced order building energy model at the core. ModelCenter and Matlab were chosen to conduct the sensitivity analysis, as they work well with parameter sweeps and data plotting. The reduced order ISO 13790 based energy model (Lee, Fei, & Augenbroe, 2011) was considered to be a good enough normative representation of the relationship between building characteristics and building energy consumption, as validation of the normative model against EnergyPlus has been conducted by researchers (Zhao, 2012), and it has been proved that there is no statistically significant difference in the building rankings that both methods produce (Kim et al., 2013). The normative energy model, based on the ISO-CEN Standard 13790 (ISO, 2008), is referred to as the EPC calculator; it is a quasi-steady state model that approximates energy flows in a building at the macro level based on a simplified description of a building and ignoring detailed dynamic effects. The EPC calculator exists in different implementations. In this study the spreadsheet version was used.

As the shape and form of residential buildings are generally consistent throughout, while commercial buildings have various building forms, hence we decide to focus on the analysis of commercial buildings. An ASHRAE prototype commercial building of a medium office was chosen for the analysis (parameters listed in Table 12), keeping the volume constant at 19,658 m^3, with a floor-to-floor height of 13 feet. The building volume was kept constant in the sense that it would be the "same" building as the number of floors change in our parameter study. As the building gets higher, the roof area gets smaller, and the impact of the roof decreases compared to the impact of the opaque façade. All parameters regarding internal heat gain (occupancy, schedules, etc.) were constant with the prototype building.

Table 12 ASHRAE Prototype Building for Medium-sized Office

Building Prototype	Medium Office
Total Floor Area (sq feet)	53,600 (163.8 ft x 109.2 ft)

Table 12 continued

Building shape	
Aspect Ratio	1.5
Number of Floors	3
Window Fraction (Window-to-Wall Ratio)	33% (Window Dimensions: 163.8 ft x 4.29 ft on the long side of facade 109.2 ft x 4.29 ft on the short side of the façade)
Window Locations	even distribution among all four sides
Shading Geometry	none
Azimuth	non-directional
Floor to floor height (feet)	13
Floor to ceiling height (feet)	9 (4 ft above-ceiling plenum)

The following set of building envelope parameters were chosen as design variables (Table 14), the uniform ranges for each parameter were determined based on a recent PhD thesis (Zhao, 2012), which were derived from the ranges listed in MacDonald's thesis (Macdonald, 2002).

When both the reflectivity and absorptance coefficient is measured for the whole hemisphere in the case of plane specimens, then the absorptance coefficient equals 1 minus reflectivity (Perrelle, Moss, & Hherbert, 1962). The Cool Roof Rating Council has specified that their "solar reflectance" is defined as the hemispherical reflectivity integrated over the solar spectrum, which is also the case for the absorption coefficient in the EPC, based on the ISO-CEN Standard 13790 (ISO, 2008).

The aspect ratio describes the proportional relationship between the building's length and width. When it is between 0 and 1, the longest wall of the building faces east and west (long axis aligned N-S); when it is over 1, the longest wall of the building faces north and south (long axis aligned E-W), as shown in Table 13.

Table 13 Aspect ratio in relationship to building orientation

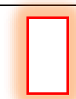
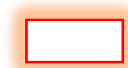
Aspect Ratio	**Building Orientation** 
0<AR<1	
AR>1	

Table 14 Ranges of design variables

Design Parameters	**Distribution**	**Range**
Roof Absorptance Coefficient	Uniform	0.05-0.88
Roof Emissivity	Uniform	0.87-0.95
Wall Absorptance Coefficient	Uniform	0.43-0.83
Wall Emissivity	Uniform	0.87-0.95
Aspect Ratio	Uniform	0.1-10
Window to Wall Ratio	Normal	Mean 0.3, Standard Deviation 0.05
Window Solar Transmittance	Uniform	0.16-0.26
Window Emissivity	Uniform	0.84-0.92
Wall U Value	Uniform	0.2-1.5

Table 14 continued

Roof U Value	Uniform	0.2-1.5
Window U Value	Uniform	1.5-4
Number of floors	Discrete	1-6

Given the feasible ranges of model variables, the next step is to generate data samples and retrieve the corresponding model outcomes for the sensitivity analysis. In order to better represent the variation of the multidimensional parameter space without generating an overwhelming quantity of samples, the Latin Hypercube Sampling (LHS) technique is chosen over the Monte Carlo Sampling, as it is considered to be more efficient for data sampling. A Latin hypercube is the generalization of this concept to an arbitrary number of dimensions, whereby each sample it the only one in each axis-aligned hyper-plane containing it, thus LHS "fills" the parameter space better and converges faster compared to the classic Monte Carlo Sampling (McKay, Beckman, & Conover, 1979).

The data samples and corresponding outcomes were generated in ModelCenter, integrating the EPC spreadsheet. A total of 1500 samples per climate zone were fed into the normative model to compute their corresponding heating and cooling loads using weather data for each corresponding city. The design variables samples and their outcomes were then used in a stepwise regression analysis for parameter sensitivity analysis (Draper & Smith, 1981). The stepwise regression analysis was conducted in Matlab.

The sensitivity analysis results are listed in Table 15, the percentage for each input parameter indicate the rank of importance compared to other parameters in determining the outputs, which are the heating and cooling loads.

Table 15 Sensitivity analysis of design parameters in affecting cooling load

		Cooling Load											
Climate Zone	**City**	**Aspect Ratio**	**No. of Floors**	**RoofAbs**	**RoofEmiss**	**RoofU**	**WallAbs**	**WallEmiss**	**WallU**	**WindowEmiss**	**WindowST**	**WindowU**	**WWR**
1A	**Miami**	21.6%	16.1%	2.5%	0.0%	4.1%	3.3%	0.0%	8.3%	0.0%	9.1%	1.3%	21.3%
2A	**Houston**	17.9%	12.5%	3.7%	0.0%	3.3%	5.0%	0.0%	9.3%	0.0%	11.0%	3.2%	17.2%
2B	**Phoenix**	21.0%	5.3%	2.6%	0.0%	10.4%	3.2%	0.0%	13.6%	0.0%	6.4%	0.1%	16.5%
3A	**Atlanta**	14.6%	8.6%	6.1%	0.0%	2.8%	6.0%	0.0%	4.6%	0.0%	13.6%	9.9%	14.8%
3B	**Las Vegas**	23.1%	7.3%	3.0%	0.0%	8.6%	2.4%	0.0%	11.6%	0.0%	8.4%	0.1%	20.1%
3C	**San Francisco**	5.5%	7.2%	4.1%	0.0%	0.4%	5.2%	0.0%	0.8%	0.0%	18.6%	29.3%	8.1%
4A	**Philadelphia**	16.3%	16.6%	2.9%	0.0%	0.7%	4.6%	0.0%	2.6%	0.0%	15.4%	8.4%	19.1%
4B	**Albuquerque**	16.2%	7.2%	5.6%	0.0%	3.9%	5.3%	0.0%	3.0%	0.2%	16.2%	8.7%	18.2%
4C	**Seattle**	4.5%	3.3%	7.2%	0.0%	0.0%	9.4%	0.0%	0.4%	0.0%	18.2%	32.3%	4.5%
5A	**Chicago**	13.9%	14.8%	4.2%	0.0%	0.8%	4.6%	0.0%	1.0%	0.0%	17.9%	11.9%	16.7%
5B	**Denver**	10.8%	5.7%	5.6%	0.0%	1.1%	6.1%	0.0%	0.6%	0.0%	18.6%	19.6%	12.7%
6A	**Minneapolis**	10.8%	19.4%	2.9%	0.0%	0.1%	3.5%	0.0%	0.2%	0.0%	17.2%	11.9%	16.8%

Table 15 continued

6B	**Helena**	8.8%	12.4%	4.3%	0.0%	0.0%	4.8%	0.0%	0.0%	0.0%	20.5%	20.4%	13.6%
7	**Duluth**	7.4%	16.8%	3.2%	0.1%	0.3%	3.7%	0.0%	0.0%	0.0%	19.8%	20.2%	13.9%
8	**Fairbanks**	8.3%	18.8%	2.5%	0.0%	0.5%	4.5%	0.0%	0.1%	0.1%	20.0%	20.7%	13.0%

Table 16 Sensitivity analysis of design parameters in affecting heating load

		Heating Load											
Climate Zone	**City**	**Aspect Ratio**	**No. of Floors**	**RoofAbs**	**RoofEmiss**	**RoofU**	**WallAbs**	**WallEmiss**	**WallU**	**WindowEmiss**	**WindowST**	**WindowU**	**WWR**
1A	**Miami**	6.6%	1.5%	0.2%	0.0%	3.5%	0.0%	0.0%	9.0%	0.0%	1.0%	11.1%	4.6%
2A	**Houston**	11.7%	0.5%	0.1%	0.0%	13.3%	0.1%	0.0%	17.7%	0.0%	0.7%	21.3%	8.7%
2B	**Phoenix**	9.8%	1.2%	0.3%	0.0%	14.0%	0.3%	0.0%	18.1%	0.0%	1.1%	23.4%	7.0%
3A	**Atlanta**	11.8%	1.3%	0.0%	0.0%	14.3%	0.2%	0.0%	21.0%	0.0%	0.8%	21.8%	8.4%
3B	**Las Vegas**	11.6%	1.9%	0.3%	0.0%	12.3%	0.3%	0.0%	21.9%	0.0%	0.9%	23.7%	7.7%
3C	**San Francisco**	11.1%	1.1%	0.6%	0.0%	12.5%	0.4%	0.0%	18.7%	0.0%	1.1%	23.4%	7.7%
4A	**Philadelphia**	12.2%	2.4%	0.1%	0.0%	13.2%	0.1%	0.0%	21.7%	0.0%	0.6%	21.2%	9.3%
4B	**Albuquerque**	11.4%	2.8%	0.1%	0.0%	12.0%	0.2%	0.0%	20.3%	0.0%	0.7%	22.0%	7.1%

Table 16 continued

4C	**Seattle**	13.1%	2.7%	0.1%	0.0%	13.3%	0.1%	0.0%	19.4%	0.0%	0.4%	21.3%	9.7%
5A	**Chicago**	12.4%	3.1%	0.0%	0.0%	13.1%	0.2%	0.0%	19.1%	0.0%	0.3%	19.3%	8.4%
5B	**Denver**	12.3%	3.6%	0.3%	0.0%	12.9%	0.2%	0.1%	20.2%	0.0%	0.5%	20.7%	7.6%
6A	**Minneapolis**	14.2%	4.5%	0.0%	0.0%	12.4%	0.1%	0.0%	21.4%	0.0%	0.2%	19.5%	8.3%
6B	**Helena**	13.9%	5.2%	0.1%	0.0%	12.7%	0.1%	0.0%	19.5%	0.0%	0.6%	20.6%	8.5%
7	**Duluth**	12.9%	4.9%	0.0%	0.0%	13.3%	0.1%	0.0%	22.0%	0.0%	0.4%	18.4%	8.7%
8	**Fairbanks**	13.5%	9.5%	0.0%	0.0%	12.5%	0.0%	0.0%	19.4%	0.0%	0.1%	16.6%	9.5%

From the results we can see that the aspect ratio of the building and number of floors rank the highest in a general sense among all 12 parameters. Window to wall ratio also ranks high, but considering most commercial buildings have their WWR close to 30%, therefore we chose to not use that as a variable in further analyses. Roof absorptance coefficient ranks low, but since the main focus of this thesis is on cool roofs and how they relate to building shape and form parameters, it was included as one of the variables for analysis as well, while holding other high-ranking parameters like U-values constant.

For the cooling load, when we filter the percentage of the aspect ratio from largest to smallest, we can see that the climate zones are listed generally from low to high, with a few odd balls mixed in between. This suggests that for cooling-dominated climates, the building shape and form ranks higher in importance when determining the cooling load of the entire building.   As for heating loads, it is basically the other way around.

Climate zor	City	AspectRati
3B	Las Vegas	23.1%
1A	Miami	21.6%
2B	Phoenix	21.0%
2A	Houston	17.9%
4A	Philadelphia	16.3%
4B	Alburqurque	16.2%
3A	Atlanta	14.6%
5A	Chicago	13.9%
6A	Minneapolis	10.8%
5B	Denver	10.8%
6B	Helena	8.8%
8	Fairbanks	8.3%
7	Duluth	7.4%
3C	SF	5.5%
4C	Seattle	4.5%

Figure 13 Aspect ratio ranking from highest to lowest; cooling loads

Climate zor	City	AspectRati
6A	Minneapolis	14.2%
6B	Helena	13.9%
8	Fairbanks	13.5%
4C	Seattle	13.1%
7	Duluth	12.9%
5A	Chicago	12.4%
5B	Denver	12.3%
4A	Philadelphia	12.2%
3A	Atlanta	11.8%
2A	Houston	11.7%
3B	Las Vegas	11.6%
4B	Alburqurque	11.4%
3C	SF	11.1%
2B	Phoenix	9.8%
1A	Miami	6.6%

Figure 14 Aspect ratio ranking from highest to lowest; heating loads

As for the ranking of the number of floors, we can see that for cooling and heating loads it is fairly mixed up, and further analysis is needed.

Climate zor	City	AspectRati	# Floo
6A	Minneapolis	10.8%	19.4%
8	Fairbanks	8.3%	18.8%
7	Duluth	7.4%	16.8%
4A	Philadelphia	16.3%	16.6%
1A	Miami	21.6%	16.1%
5A	Chicago	13.9%	14.8%
2A	Houston	17.9%	12.5%
6B	Helena	8.8%	12.4%
3A	Atlanta	14.6%	8.6%
3B	Las Vegas	23.1%	7.3%
4B	Alburqurque	16.2%	7.2%
3C	SF	5.5%	7.2%
5B	Denver	10.8%	5.7%
2B	Phoenix	21.0%	5.3%
4C	Seattle	4.5%	3.3%

Figure 15 Number of floors ranking from highest to lowest; cooling loads

Climate zor	City	AspectRati	# Floo
8	Fairbanks	13.5%	9.5%
6B	Helena	13.9%	5.2%
7	Duluth	12.9%	4.9%
6A	Minneapolis	14.2%	4.5%
5B	Denver	12.3%	3.6%
5A	Chicago	12.4%	3.1%
4B	Alburqurque	11.4%	2.8%
4C	Seattle	13.1%	2.7%
4A	Philadelphia	12.2%	2.4%
3B	Las Vegas	11.6%	1.9%
1A	Miami	6.6%	1.5%
3A	Atlanta	11.8%	1.3%
2B	Phoenix	9.8%	1.2%
3C	SF	11.1%	1.1%
2A	Houston	11.7%	0.5%

Figure 16 Number of floors ranking from highest to lowest; heating loads

From this sensitivity analysis we decided on three building parameters that either ranked of highest importance or was considered important for cool roofs - roof absorptance coefficient, aspect ratio and number of floors, and the next step is to further analyze these parameters and examine their effects on heating and cooling load and consumption.

CHAPTER 5

EVALUATING THE EFFECTS OF DESIGN PARAMETERS

From the sensitivity analysis, we have come to the conclusion that the roof absorptance coefficient, aspect ratio and number of floors are the three design variables that have a relatively large effect on heating and cooling loads. Therefore we chose to look at them individually and combined together. In order to evaluate the actual effect of these three design parameters have on heating and cooling loads, numerous parametric studies were conducted in ModelCenter. The total building volume was still kept at a constant value, therefore the higher the building gets, the smaller its roof area becomes. All other parameters were kept constant at ASHRAE 90.1 code prescriptive values, as shown in Table 17.

Table 17 ASHRAE 90.1 Building parameter prescriptive values by climate zone

Climate Zone	Roof U Value W/m^2K	Wall U Value W/m^2K	Window U Value W/m^2K
1	0.37	0.64	6.81
2	0.37	0.64	4.26
3	0.37	0.64	3.69
4	0.37	0.64	3.12
5	0.37	0.64	3.12
6	0.37	0.64	3.12
7	0.37	0.32	2.56
8	0.28	0.32	2.56

5.1 Parametric study of aspect ratio and loads

A parametric study of the relationship between aspect ratio and heating and cooling loads for all 15 cities were conducted. The range for the aspect ratio was from 0.5 to 2 as this is common for typical commercial buildings. From Figure 17 and Figure 18 (which is for Las Vegas) it can be derived that in order to achieve a minimum value in either heating or cooling loads, the aspect ratio of the building would need to be around 1, i.e. the more "square" the shape of a building is, the more likely it is to achieve less heating and cooling loads. There is a similar trend for the other 14 cities, listed in the Appendix. Note that when the aspect ratio is between 0 and 1, the longest wall of the building faces east and west (long axis aligned N-S); when it is above 1, the longest wall of the building faces north and south (long axis aligned E-W).

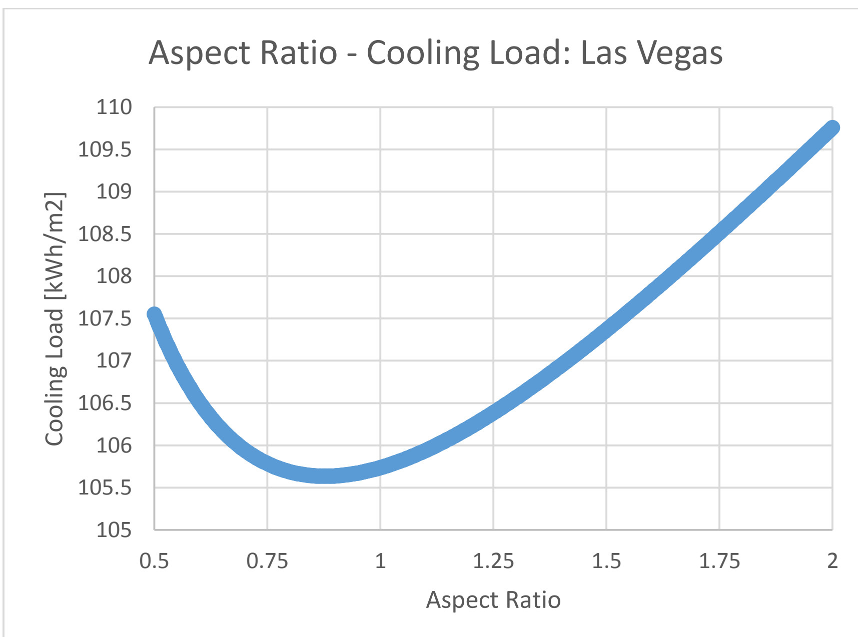


Figure 17 Aspect Ratio – Cooling Load; Las Vegas

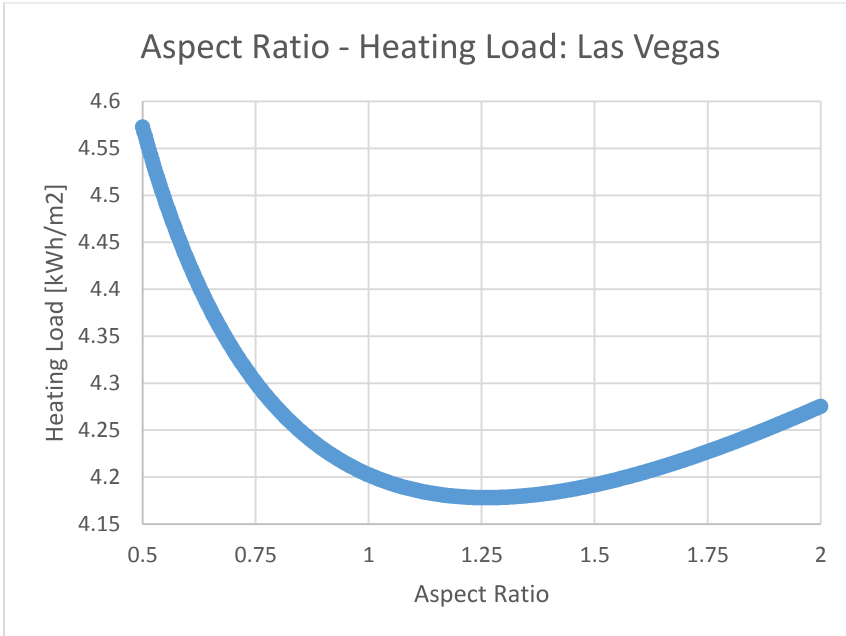


Figure 18 Aspect Ratio – Heating Load; Las Vegas

Figure 17 and 18 indicate that the cooling load is higher when the longest wall of the building faces north and south compared to facing east and west; while heating load is lower. This is reasonable as south-facing walls receive more sunlight and heat gain from outside than east and west-facing walls.

5.2 Parametric study of no. of floors and loads

As for the number of floors, we can see that when the building volume is kept constant at 19,658 m^3, as the building grows higher, the cooling load increases, but for heating load the minimum value is when it is a two-story building, then the heating load increases from the third story up. However, the general trend is that the loads increase as the building height increases. This can be explained by the increase in total surface area as the building grows taller when keeping the total volume at a constant value, as shown in Table 18. Since the window to wall ratio is also held constant at 30%, hence the total window area increases, therefore increasing total building loads.

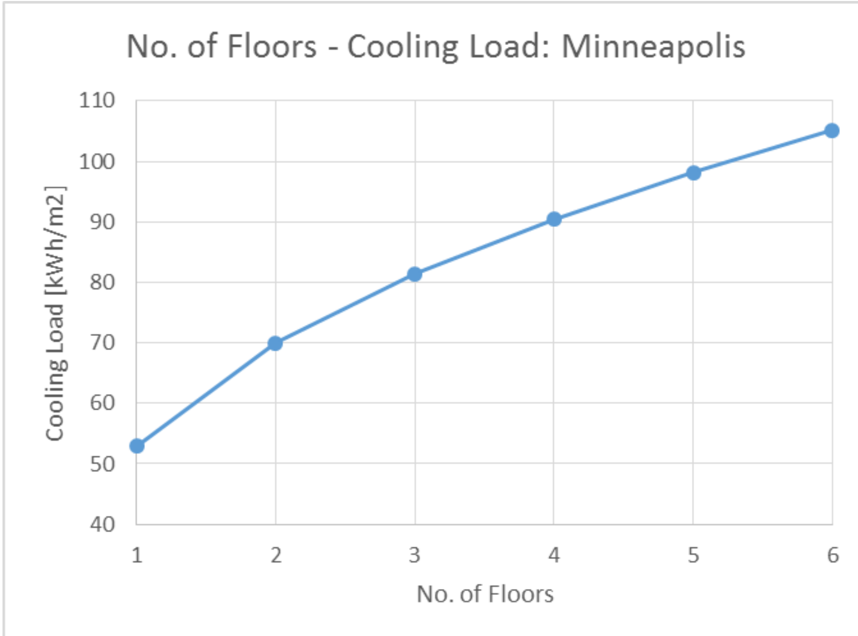


Figure 19 No. of Floors – Cooling Load; Minneapolis

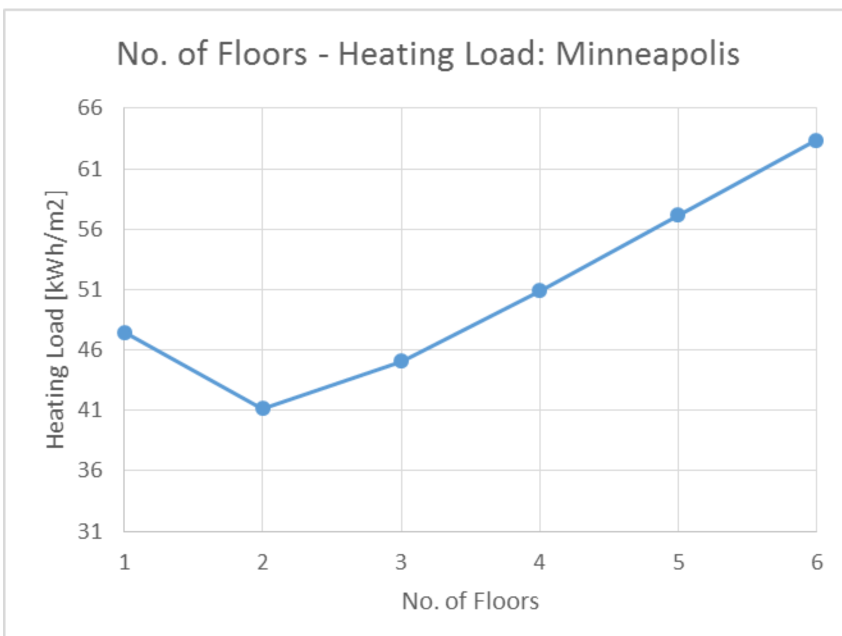


Figure 20 No. of Floors – Heating Load; Minneapolis

Table 18 No. of Floors and Surface Area

No. of Floors	Total Surface Area [m^2]	Surface Area : Volume
1	1531	0.08
2	2166	0.11
3	2653	0.13
4	3063	0.16
5	3424	0.17
6	3751	0.19

5.3 Parametric study of roof absorptance coefficient and loads

For roof absorptance coefficient, a three-dimensional graph was plotted, including the influence of another variable – roof emissivity. From the graphs below we can see that higher roof absorptance coefficient (i.e. lower roof albedo) will lead to lower heating loads, which is reasonable since the additional heat gain through the roof offsets part of the heat losses in winter; as for cooling loads it is the other way around - higher roof absorptance coefficient leading to higher cooling loads, as more solar radiation is absorbed and increases the total heat gain in summer. The range of roof emissivity is fairly small compared to roof absorptivity, but we can still see that the heating loads increases while the cooling loads decreases with an increase in roof emissivity, which is expected.

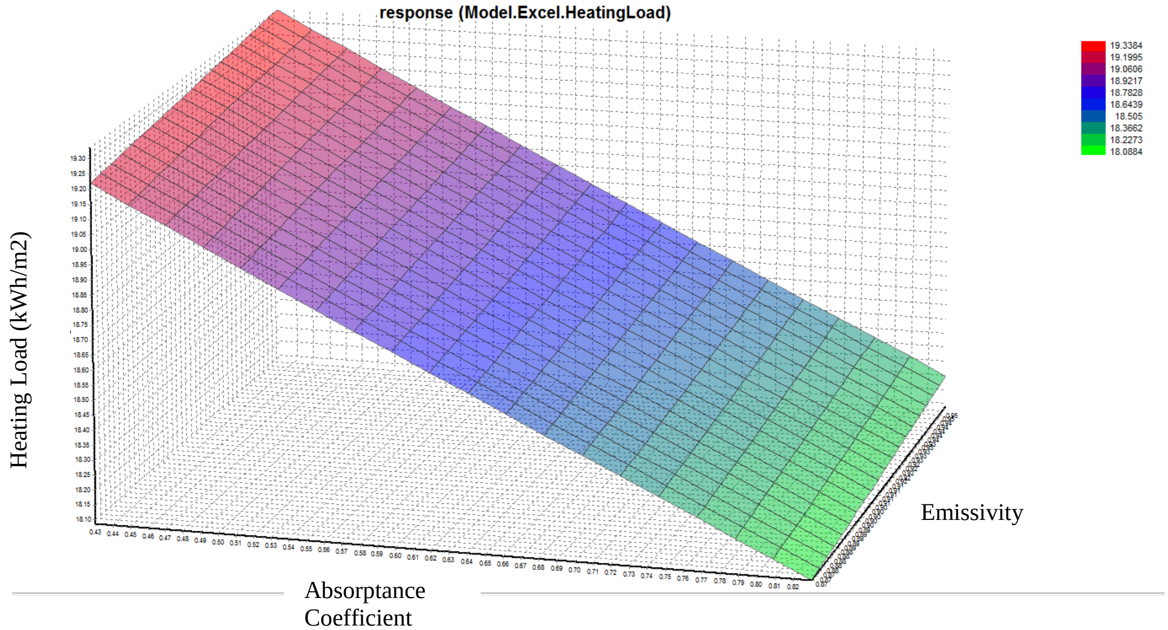


Figure 21 Roof Absorptance Coefficient – Emissivity - Heating Load; Atlanta

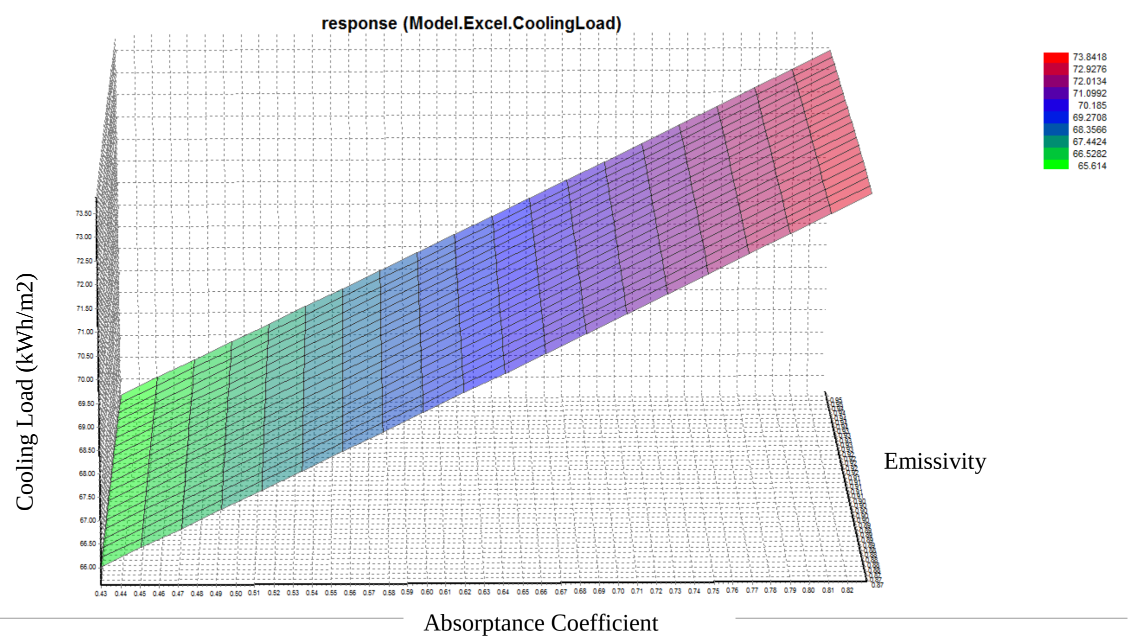


Figure 22 Roof Absorptance Coefficient – Emissivity - Cooling Load; Atlanta

5.4 Parallel Coordinates Plots for the three variables

Since roof emissivity ranks a low percentage in the sensitivity analysis in Chapter 4, therefore we decided to take out this variable and focus on aspect ratio, number of floors and roof absorptance coefficient. These three parameters were plotted in a single graph, which is a parallel coordinates plot. These plots were done for the 9 cities that had a great change in loads when roof absorptance coefficient, aspect ratio and number of floors varied, listed in Table 19 below:

Table 19 Nine Cities for further analysis

Climate Zone	City
1A	Miami
2B	Phoenix
3A	Atlanta
3B	Las Vegas
4A	Philadelphia
4C	Seattle
5B	Denver
6A	Minneapolis
8	Fairbanks

The ranges for the three variables were 0.1-10 for aspect ratio, 1-6 for no. of floors, and 0.05-0.88 for roof absorptance coefficient.

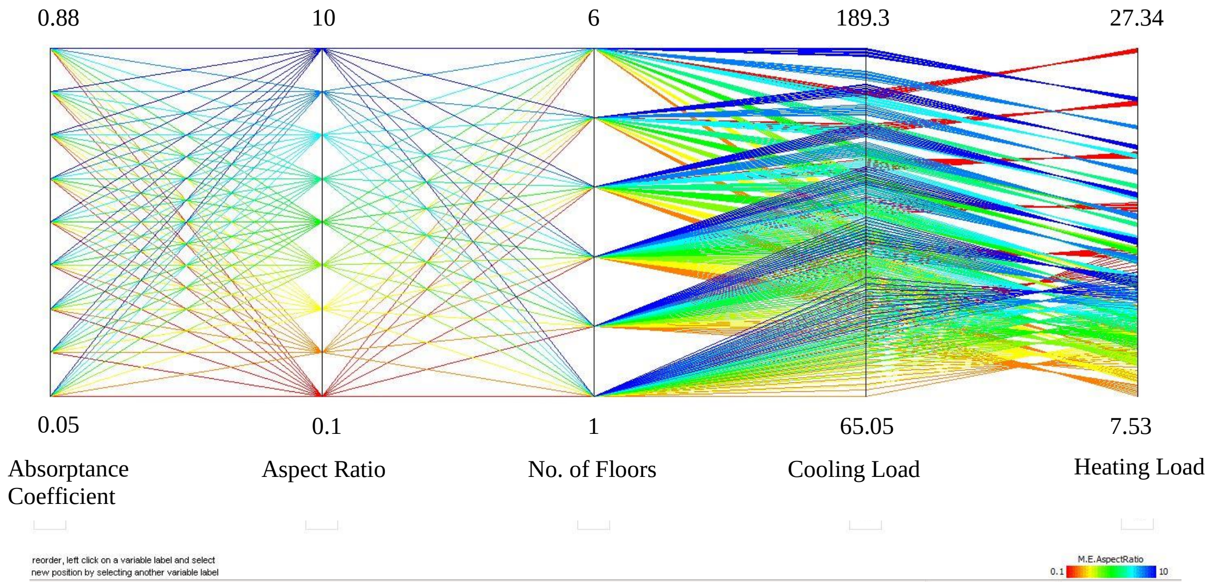


Figure 23 Aspect ratio as colored lines; Atlanta

From Figure 23 we can see that as the number of floors increase, the lines for a specific aspect ratio become tighter, and the spread in loads become greater. This suggests that for buildings with the same volume, as the number of floors increases, the effect of changes in aspect ratio will become more and more profound. Also, for buildings with the same volume, changes in roof absorptance coefficient will show less of an impact on the heating and cooling loads in high-rise buildings than an equal-volume low-rise building. This is reasonable as when the volume is kept constant, taller buildings will have a smaller roof, and the walls will represent a large portion of the envelope.

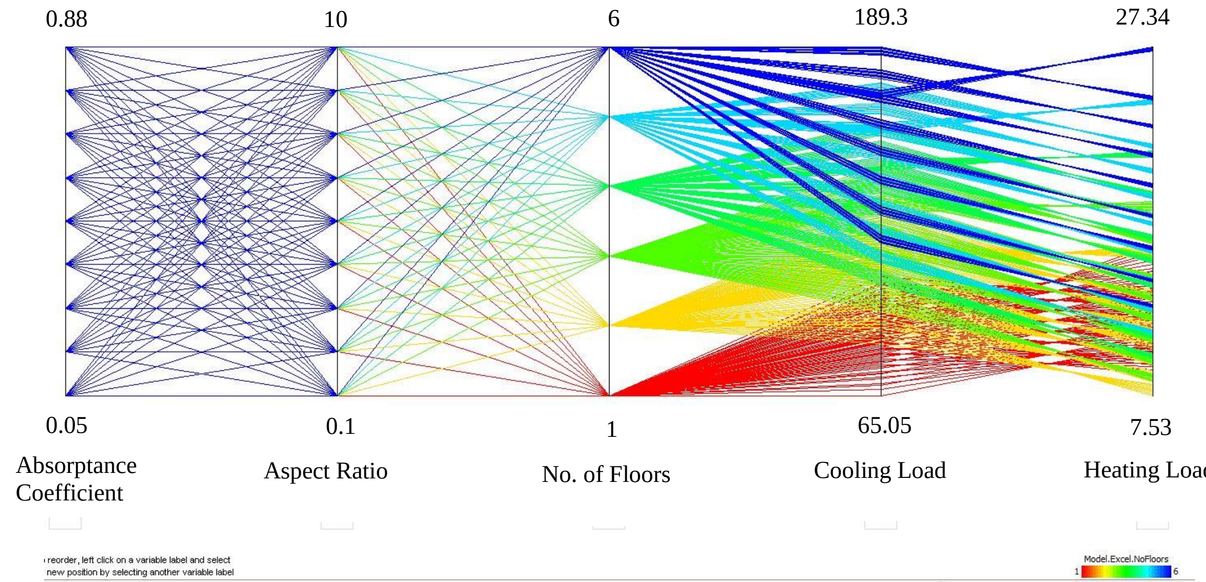


Figure 24 Number of floors as colored lines; Atlanta

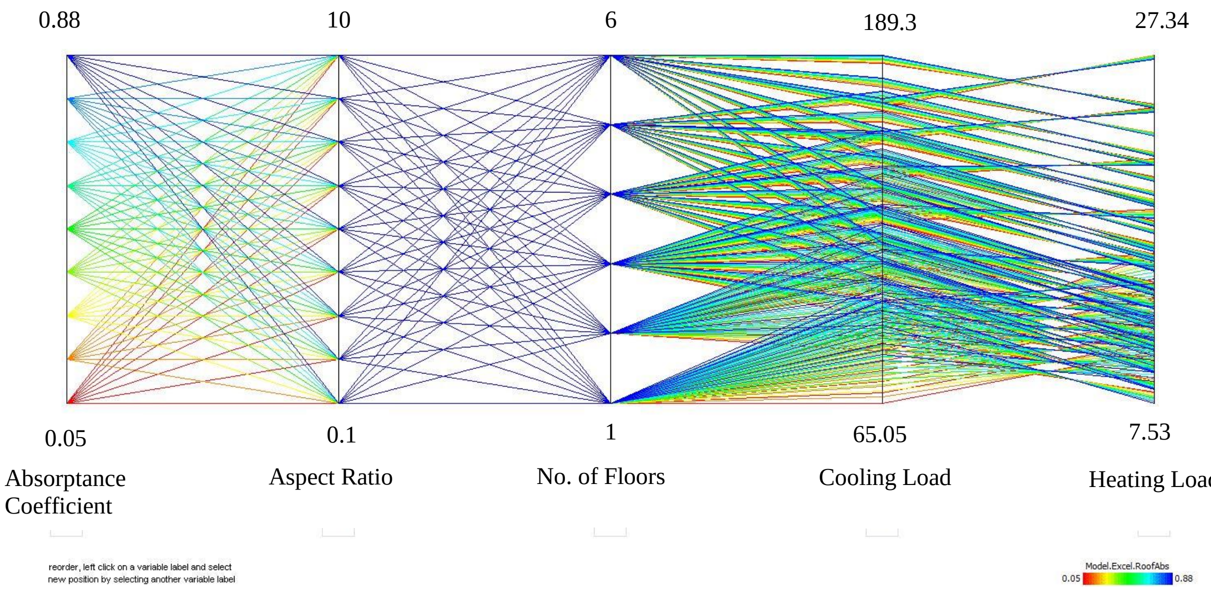


Figure 25 Roof absorptance coefficient as colored lines; Atlanta

It is hard to interpret the roof absorptance coefficient graph as lines get jumbled up and therefore needs a smaller scale. In order to narrow down the data, we removed the extreme aspect ratios and only plot ratios between 0.5 and 2. Also, in order to see how the trends regarding the aspect ratio evolve with a given number of floors, coordinates with only the roof absorptance coefficient and aspect ratio as design variables were plotted for each floor respectively, from floor 1 to 6, total building volume held constant, for each of the nine cities.

Table 20 Parallel coordinates plot for Philadelphia; climate zone 4A

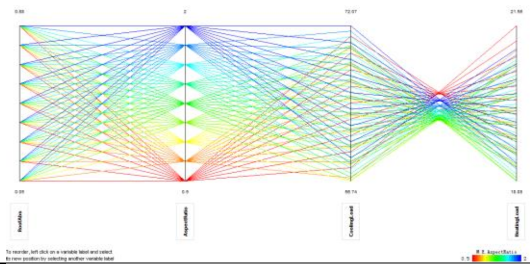
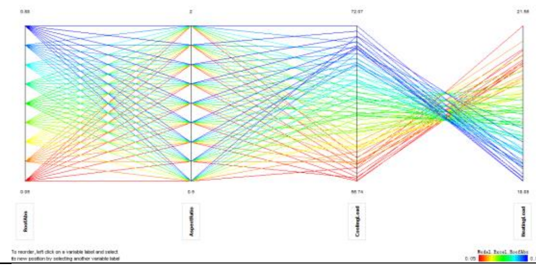
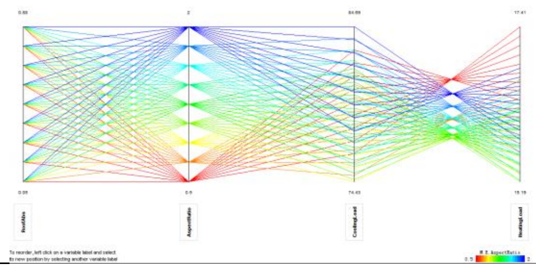
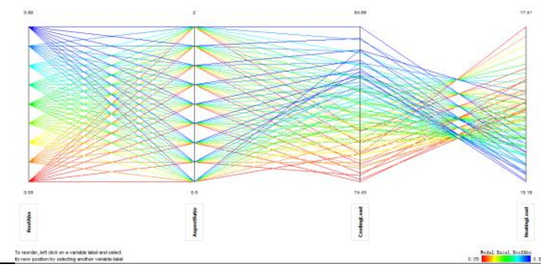
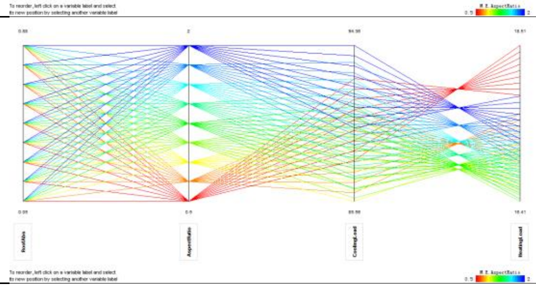
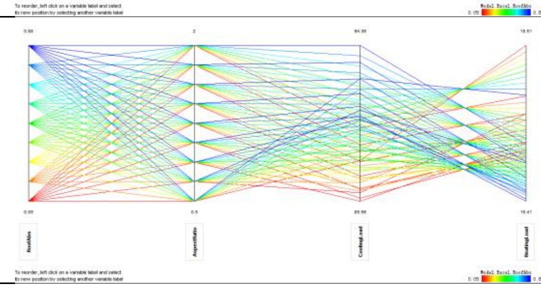
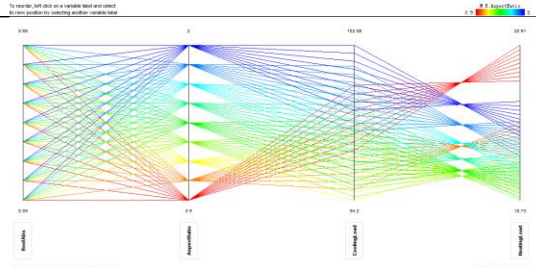
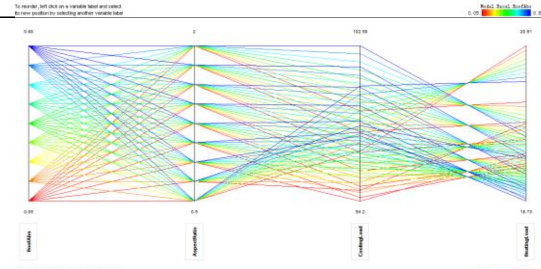
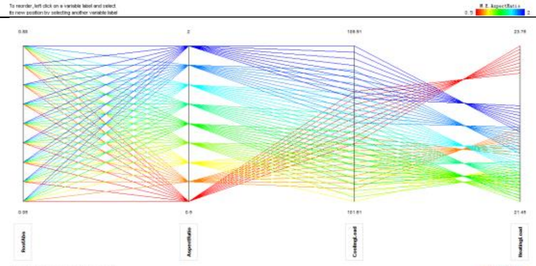
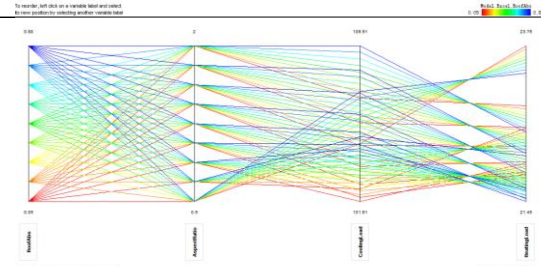
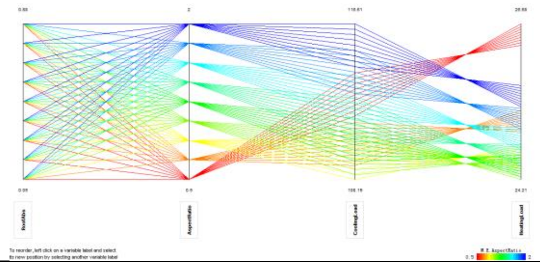
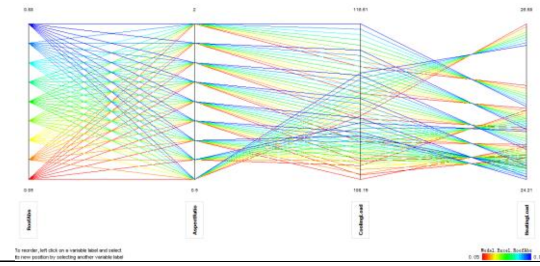
No. of Floors	Lines colored by Aspect Ratio Aspect Ratio Range [0.5-2]	Lines colored by Roof Absorptance Coefficient Roof Abs. Coefficient Range [0.05-0.88]
1		
2		
3		
4		
5		

Table 20 continued

6		

As Philadelphia was one of the case studies that yielded a negative savings over the year, it is used as an example here (Table 20) to see the effect of aspect ratio and roof absorptance coefficient on heating and cooling loads. We can see that for a lower building, roof absorptance coefficient has a more profound effect on heating and cooling loads, as the roof area takes up a bigger portion of the building envelope. For a higher building, aspect ratio has a much larger effect on loads, and cool roofs will not have as big of an effect on loads. We can conclude that for a high-rise commercial building, an aspect ratio closer to 1 will yield more savings than applying a white roof coating; this is fairly important in the design stage.

For a given number of floors, when comparing aspect ratio and roof absorptance coefficient (black or white roof), we can see that for a black roof, its cooling load is higher while heating load is lower than that for a white roof for the same aspect ratio (same building form).

For Atlanta, plots are illustrated in Table 21. The trends are similar, indicating the same conclusions. Results for other seven cities are listed in the appendix.

Table 21 Parallel coordinates plots for Atlanta; climate zone 3A

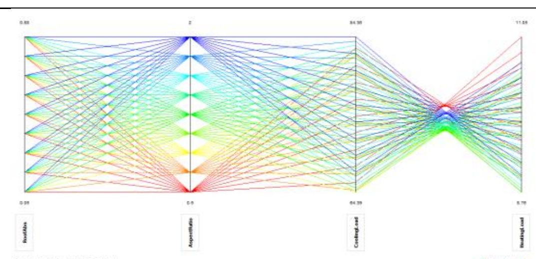
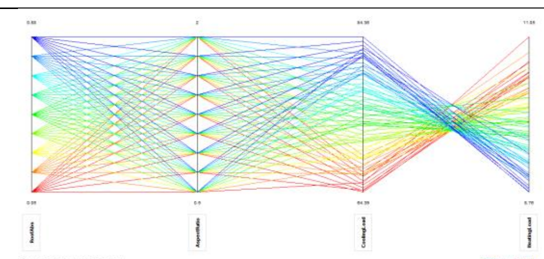
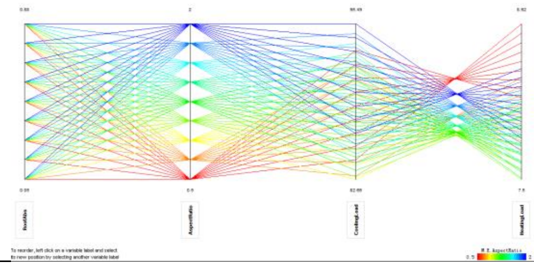
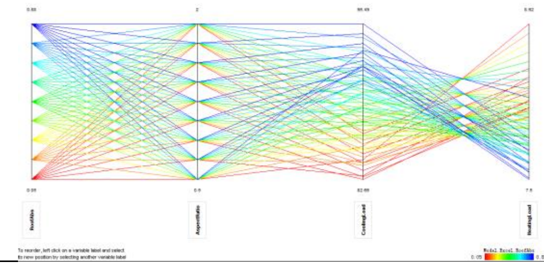
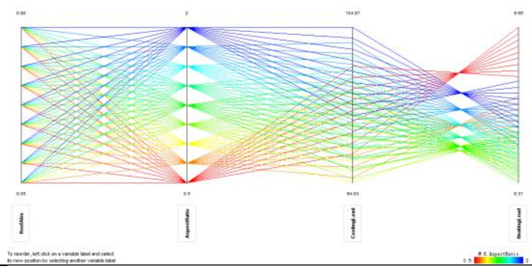
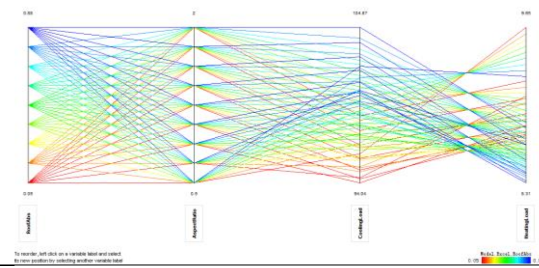
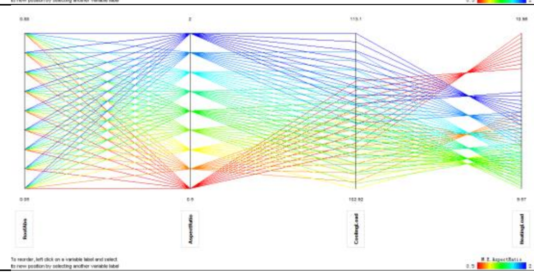
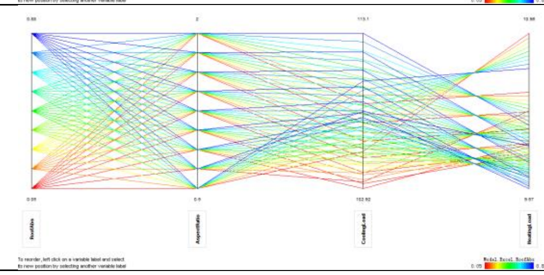
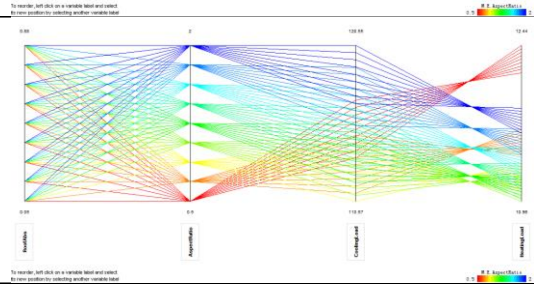
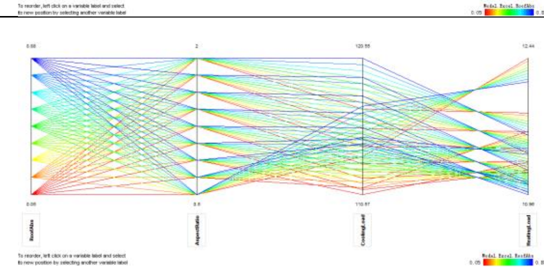
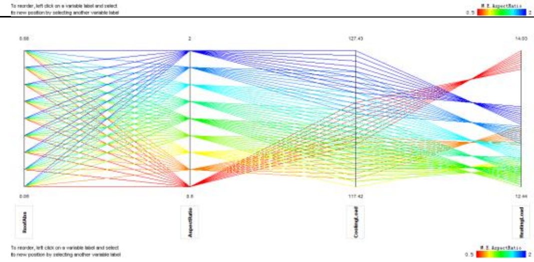
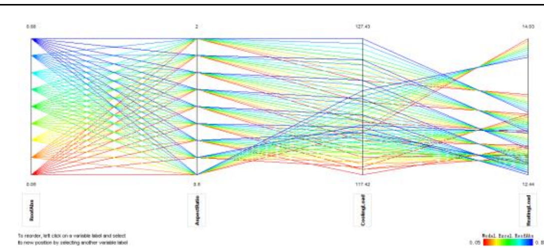
No. of Floors	Lines colored by Aspect Ratio	Lines colored by Roof Absorptance Coefficient
1		

Table 21 continued

2		
3		
4		
5		
6		

When considering from the costs perspective, parallel coordinates plots can also be illustrated as follows (Table 22), using Minneapolis as an example. The axes are roof absorptance coefficient, aspect ratio, and total costs respectively, from left to right. The total costs were calculated by assuming a heat pump system for cooling, gas furnace for heating, cooling COP of 3, heating COP of 0.7, electricity price of $0.11/kWh, and gas price of $0.04/kWh.

From the plots we can see the same trends as the graphs above, an aspect ratio closer to 1 would yield a minimum total cost, and as the number of floors increase a black roof with a better aspect ratio would yield a lower cost than a white roof with extreme aspect ratios.

Table 22 Parallel coordinates plots for Minneapolis; climate zone 6A

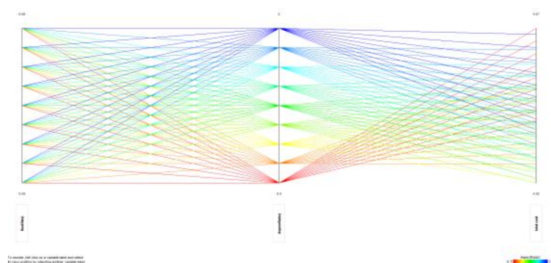
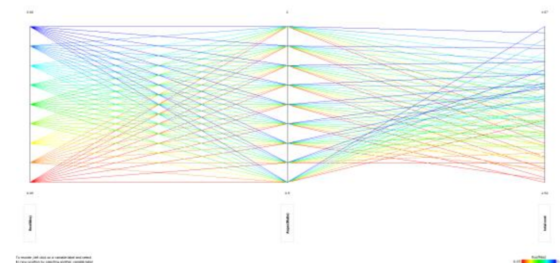
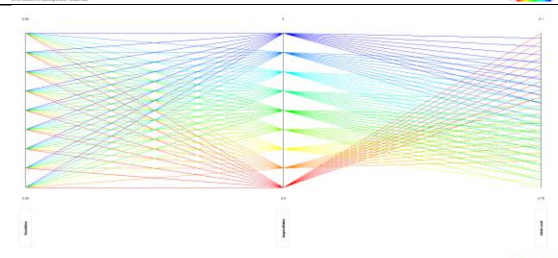
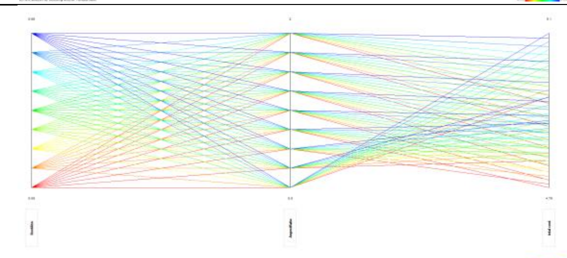
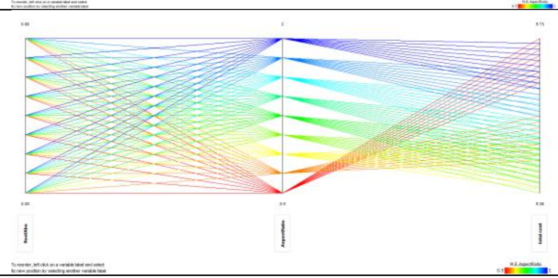
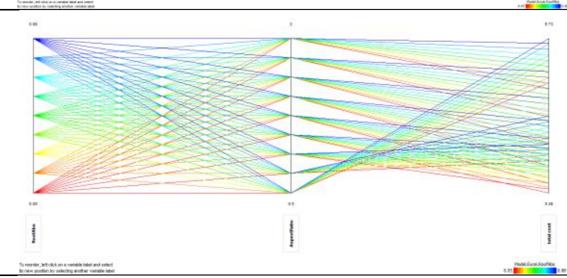
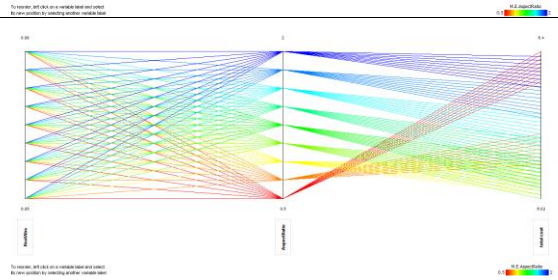
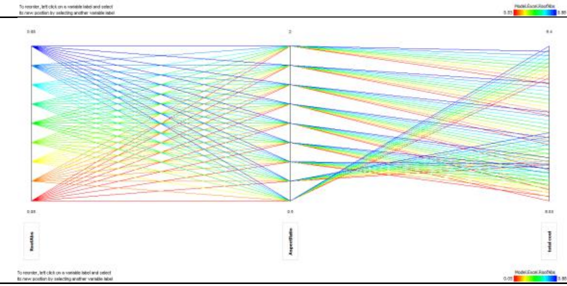
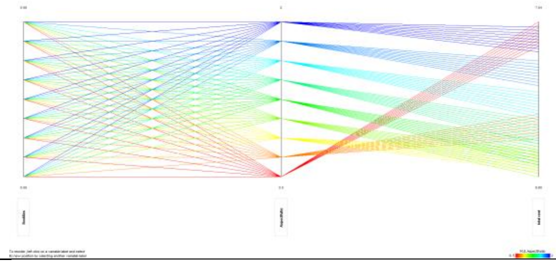
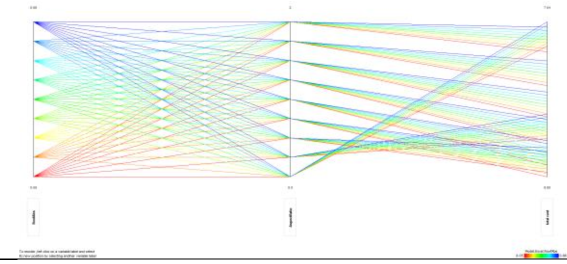
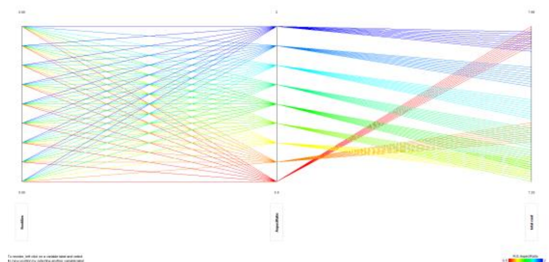
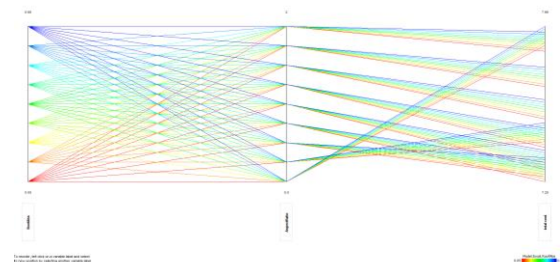
No. of floors	Lines colored by Aspect Ratio	Lines colored by Roof Absorptance Coefficient
1		
2		
3		
4		

Table 22 continued

5		
6		

CHAPTER 6

SIMPLE COOL ROOF NET SAVINGS MODEL

In order to evaluate the savings in terms of costs of cool roofs compared to conventional black roofs in different climate zones, a simple "COP ratio model" was developed.

For a given building in a specific city, the annual price for heating and cooling when it has a black roof:

$$P_b = \frac{L_{h,b}}{COP_h} \times P_h + \frac{L_{c,b}}{COP_c} \times P_c \tag{6.1}$$

The annual price for heating and cooling when it has a white roof:

$$P_b = \frac{L_{h,b}}{COP_h} \times P_h + \frac{L_{c,b}}{COP_c} \times P_c$$

$L_{h,b}$ – heating load for a black roof;

$L_{h,w}$ – heating load for a white roof;

$L_{c,b}$ – cooling load for a black roof;

$L_{c,w}$ – cooling load for a white roof;

P_h – price for heating, \$/therm;

P_c – price for cooling, \$/kWh;

COP_c – cooling system efficiency;

COP_h – heating system efficiency;

P_b – annual price for heating and cooling for a black roof;

P_w – annual price for heating and cooling for a white roof.

Since it is a given building, hence aspect ratio, number of floors, system type (natural gas or electricity) and system efficiency are set parameters. Therefore, when $P_b - P_w > 0$, or

$$\frac{COP_h}{COP_c} > \frac{(L_{h,b} - L_{h,w}) \times P_h}{(L_{c,b} - L_{c,w}) \times P_c} \tag{6.2}$$

It would be beneficial in operating cost to use a white roof instead of a black roof.

Define $\frac{(L_{h,b}-L_{h,w})\times P_h}{(L_{c,b}-L_{c,w})\times P_c}$ as Roof Selection Indicator (RSI).

The surface properties for a code-required black roof and white roof is listed in Table 23 below.

Table 23 Black Roof and White Roof Surface Properties

Roof	Absorptance Coefficient	Emissivity	Solar Reflectance
Black Roof	0.88	0.70	0.12
White Roof	0.3	0.75	0.7

The ASHRAE prototype medium office building was used to calculate loads in the normative model, parameters listed in Table 24 below. A prototype building model was chosen as it would be more representative and would apply to most medium-sized commercial building cases.

Table 24 ASHRAE Prototype Medium Office Building

Prototype	Medium Office Building
No. of Floors	3
Aspect Ratio	1.5
Building Volume [m^3]	19,658
Roof Area [m^2]	1654

The price for heating (gas) is \$1.1/therm, or \$0.04/kWh, and the price for cooling (electricity) is \$0.11/kWh, using average prices across the U.S. The energy factor for gas is 1.08 while for electricity it is 3.17. Note that electricity is around 3 times of that of gas in terms of both cost and emissions.

Using Minneapolis as an example, for a well-insulated building with a roof U-Value of 0.37 W/m^2K (ASHRAE code requirements):

Table 25 Parameters for a well-insulated ASHRAE prototype commercial building in Minneapolis

Parameter	Heating (Gas)	Cooling (Electricity)
Loads, black roof [kWh/m^2]	43.85	83.44
Loads, white roof [kWh/m^2]	44.53	80.42
COP	0.7	3
Price	0.04	0.11

Since

$$\frac{COP_h}{COP_c} = 0.23 > \frac{(L_{h,b} - L_{h,w}) \times P_h}{(L_{c,b} - L_{c,w}) \times P_c} = 0.07$$

It is beneficial in terms of cost to put a white roof coating on a medium-sized well-insulated commercial building in Minneapolis that has a low-efficiency heating system and a medium-efficiency cooling system.

If the building has poor roof insulation, the savings in summer is greater but the penalty in winter also increases, therefore to evaluate the effects of a white roof on a building with no roof insulation, the same steps were applied, still using Minneapolis as an example. Assuming that the uninsulated building has a roof U-value of 2.50 W/m^2K:

Table 26 Parameters for an uninsulated ASHRAE prototype commercial building in Minneapolis

Parameter	Heating (Gas)	Cooling (Electricity)
Loads, black roof [kWh/m^2]	98.47	85.73
Loads, white roof [kWh/m^2]	104.82	67.66

Table 26 continued

COP	0.7	3
Price	0.04	0.11

Since

$$\frac{COP_h}{COP_c} = 0.23 > \frac{(L_{h,b} - L_{h,w}) \times P_h}{(L_{c,b} - L_{c,w}) \times P_c} = 0.11$$

It is still beneficial in terms of cost to put a white roof coating on a medium-sized uninsulated commercial building in Minneapolis, but the net savings in dollars is less than for a well-insulated building, as the heating penalty is greater.

The same procedure was applied to all 9 cities, with the same system efficiencies of 0.7 (heating, boiler) and 3 (cooling, heat pump), and roof U-Values that met the code requirements of the corresponding climate zone, and it was found that for a well-insulated ASHRAE prototype medium-sized office building (roof insulation meeting ASHRAE code requirements), it was always beneficial economically to use a white roof, as shown in Table 27 below.

Table 27 Comparison of black and white roofs of an ASHRAE prototype office building using Simple Model

City	Climate Zone	Black Roof		White Roof		COP Ratio, or Left Side of Formula	RSI	Cool Roof Application
		Heating Loads kWh/m^2	Cooling Loads kWh/m^2	Heating Loads kWh/m^2	Cooling Loads kWh/m^2			
Miami	1A	0.00	175.05	0.00	169.94	0.7/3 = 0.23	0.000	Yes
Phoenix	2B	0.95	177.81	1.03	170.68		0.004	Yes
Atlanta	3A	8.40	102.41	8.69	98.03		0.023	Yes
Las Vegas	3B	3.41	150.17	3.61	144.62		0.012	Yes
Philadelphia	4A	16.58	92.07	17.05	88.74		0.049	Yes

Table 27 continued

Seattle	4C	10.80	65.26	11.13	61.38		0.029	Yes
Denver	5B	19.12	79.12	19.82	74.90		0.057	Yes
Minneapolis	6A	43.85	83.44	44.53	80.42		0.078	Yes
Fairbanks	8	92.40	61.27	92.88	59.36		0.086	Yes

Table 28 Comparison of sum of loads and consumption between black roofs and white roofs of an ASHRAE prototype office building

City	Climate Zone	Black Roof			White Roof			Cool Roof Application
		Sum of Loads kWh/m^2	Sum of Consumption kWh/m^2	Annual Cost \$/m^2	Sum of Loads kWh/m^2	Sum of Consumption kWh/m^2	Annual Cost \$/m^2	
Miami	1A	175.05	58.35	6.42	169.94	56.65	6.23	Yes
Phoenix	2B	178.76	60.62	6.57	171.71	58.36	6.32	Yes
Atlanta	3A	110.81	46.14	4.24	106.72	45.09	4.09	Yes
Las Vegas	3B	153.58	54.93	5.70	148.23	53.36	5.51	Yes
Philadelphia	4A	108.64	54.37	4.32	105.79	53.94	4.23	Yes
Seattle	4C	76.06	37.18	3.01	72.51	36.36	2.89	Yes
Denver	5B	98.24	53.69	3.99	94.73	53.29	3.88	Yes
Minneapolis	6A	127.29	90.45	5.57	124.95	90.43	5.49	Yes
Fairbanks	8	153.67	152.42	7.53	152.24	152.48	7.48	Yes

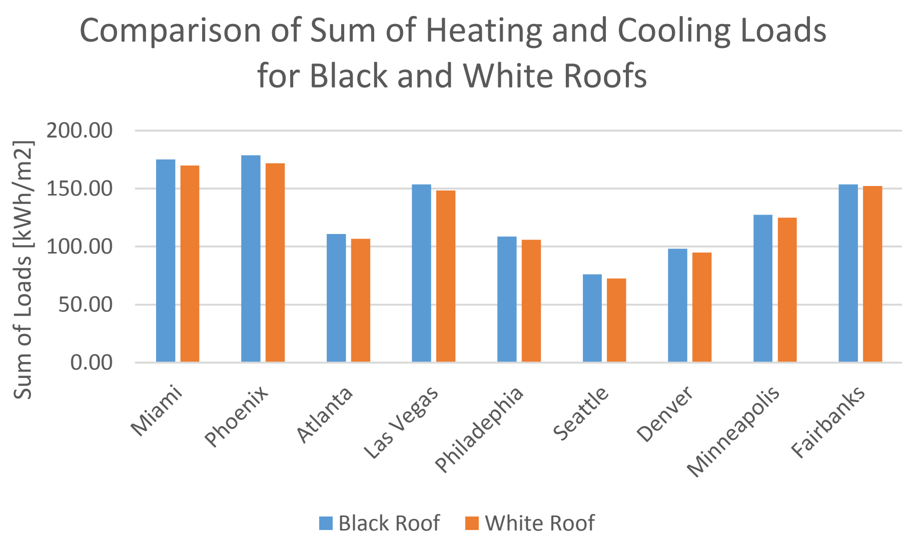


Figure 26 Comparison of sum of loads for black and white roofs

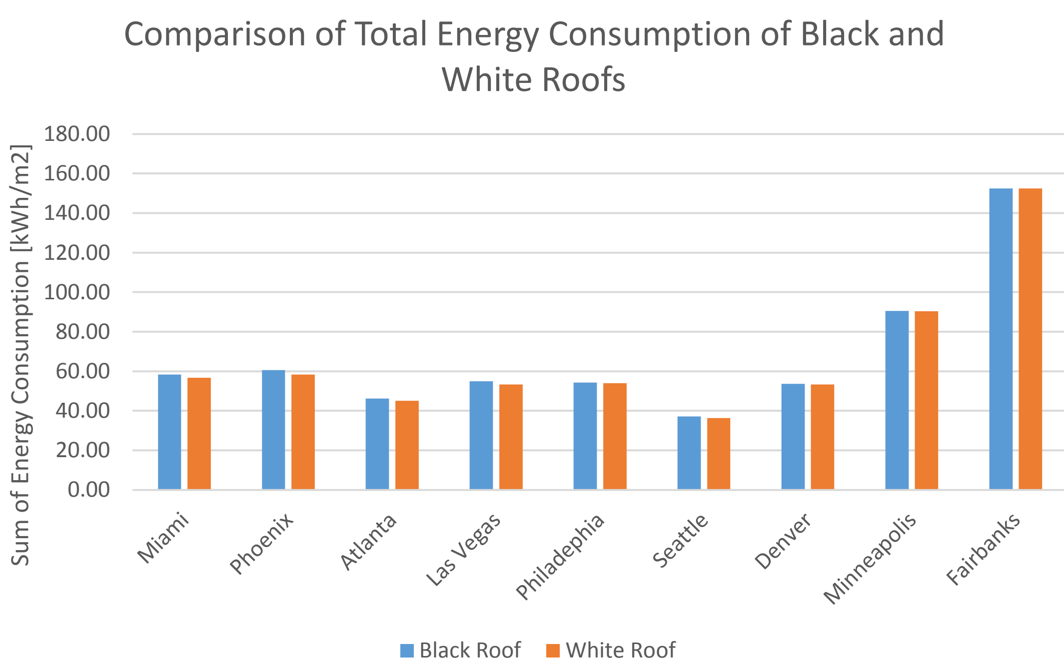


Figure 27 Comparison of total energy consumption of black and white roofs

It is interesting to see that the sum of loads (heating and cooling) is always larger for a black roof than for a white roof. For consumption however, Fairbanks is the only city that has a higher energy consumption for white roofs than black roofs, however once taken the price of heating and cooling into account, it is still beneficial cost-wise to use a white roof, though the advantage is very limited.

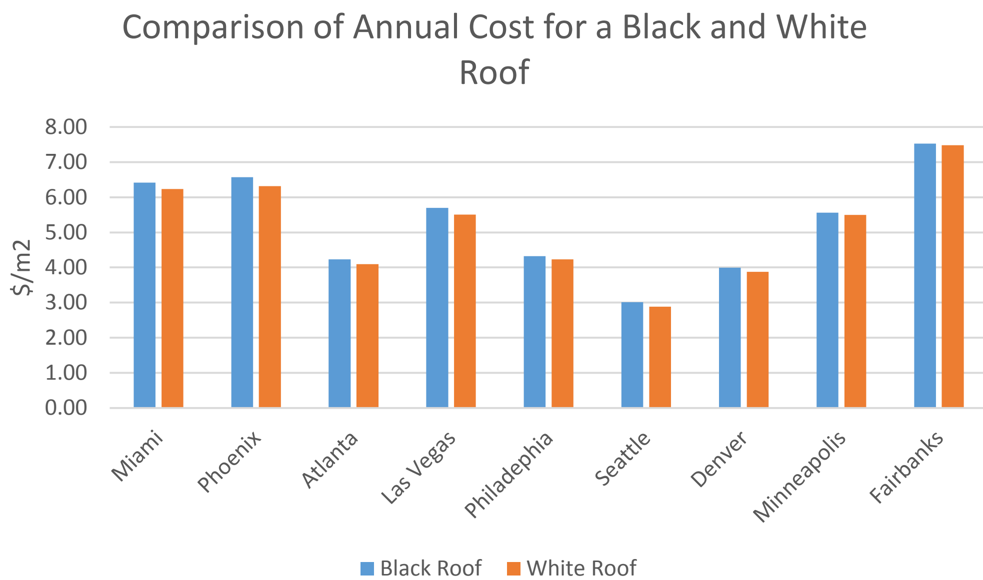


Figure 28 Annual Cost for a Black and White Roof

From Figure 26 through 28 we can conclude that for a medium-sized commercial building, the sum of heating and cooling loads is always greater for black roofs than for white roofs, for energy consumption this conclusion is not that definite as northernmost climates such as Fairbanks may have a higher energy consumption for white roofs, but in terms of cost it seems that it is always beneficial to use a white roof, disregarding the climate zone the building is in.

However, in ASHRAE 90.1, a table (shown in Figure 29) that discusses the insulation levels for high albedo roofs seems to imply that cool roofs are not permitted in climate zones 4 and above, which conflicts with the results from the case studies, Cool Roof Calculator results, and with the results from the simple COP ratio model. So far no documentation was found on how this chart was developed, hence no solid conclusion can be made at this point.

TABLE 5.5.3.1 High Albedo Roof Insulation

Climate Zone	Opaque Elements (Roofs)	Nonresidential		Residential	
		Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
1	Insulation entirely above deck	U-0.082	R-12.0 c.i.	U-0.081	R-12.0 c.i.
	Metal building	U-0.084	R-13	U-0.084	R-13.0
	Attic and other[a]	U-0.044	R-24.0	U-0.035	R-30.0
2	Insulation entirely above deck	U-0.076	R-13.0 c.i.	U-0.076	R-13.0 c.i.
	Metal building	U-0.078	R-13.0	U-0.078	R-13.0
	Attic and other[a]	U-0.041	R-25.0	U-0.032	R-30.0
3	Insulation entirely above deck	U-0.074	R-13.c.i.	U-0.074	R-13.0 c.i.
	Metal building	U-0.076	R-16	U-0.076	R-16.0
	Attic and other[a]	U-0.040	R-25.0	U-0.032	R-30.0
4, 5, 6, 7, 8	All roof opaque elements	NP	NP	NP	NP

NP = Not permitted.
[a]Excludes roofs over ventilated attics, or roofs over semiheated spaces, or roofs over conditioned spaces that are not cooled spaces.

Figure 29 ASHRAE 90.1 Insulation Level for High Albedo Roofs (ASHRAE, 2007)

CHAPTER 7

CONCLUSION AND DISCUSSION

In this study, we examined the effect of cool roofs on commercial and residential buildings in each climate zone, from the monitored case studies, DOE-2 simulations, Cool Roof Calculator to the simple COP ratio model, we have found that for medium-sized commercial buildings, a cool roof is always beneficial economically, though in northernmost areas like Fairbanks the net savings is fairly small. However, in residential buildings especially single story houses, the heating penalty may outweigh the cooling savings, as the internal heat gain is smaller due to shorter “operation” hours and lighting schedules, etc. DOE-2 simulations tend to underestimate the cooling energy savings however, so the overall net savings in dollars over the year may be greater than estimated. Lower insulation also yields greater savings in cooling energy, but may sustain a larger heating penalty.

As the Cool Roof Calculator does not take the building use, form and shape into account, a sensitivity analysis was conducted to rank the importance of various building parameters against one another. It was concluded that the aspect ratio and number of floors have a high impact on building loads, these two parameters and also roof absorptance coefficient were chosen as key variables for further parametric analyses, which were to evaluate the impact of various building parameters on building loads.

The parametric studies indicated that when the total building volume is kept constant, as the number of floors increase, the effect of changes in aspect ratio will become more and more profound. Also, for buildings with the same volume, changes in roof absorptance coefficient will show less of an impact on the heating and cooling loads in high-rise buildings than an equal-volume low-rise building. The reason for this is that when the building volume is kept constant, taller buildings will have a smaller roof area, and the walls will represent a larger portion of the envelope.

From the results of the comparison based on the simple COP ratio model, we can conclude that for a medium-sized commercial building, the sum of heating and cooling loads is always greater for black roofs than for white roofs, disregarding the climate zone that the building is in. Except for the most northern climates such as Fairbanks, the energy consumption is also always greater for black roofs than white roofs. In terms of cost, it is also always beneficial to use a white roof, but cities in northern climates may have little advantage.

The limitations of this study is that it uses a normative building energy model (EPC) for load calculations, which is better for ordinal analysis rather than cardinal analysis. Therefore, the numbers of actual values may not be that accurate and the savings from a white roof may not be as much, or the heating penalties may not be as negligible. It is still possible for a black roof to be better than a white one over the year, as suggested in the case studies.

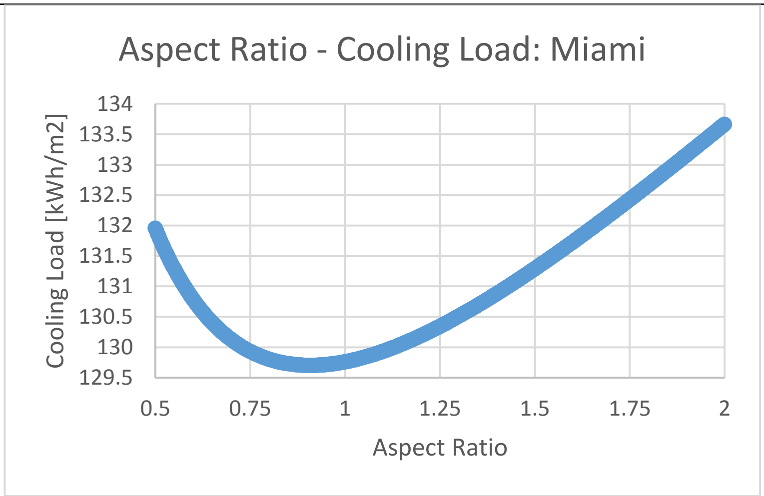
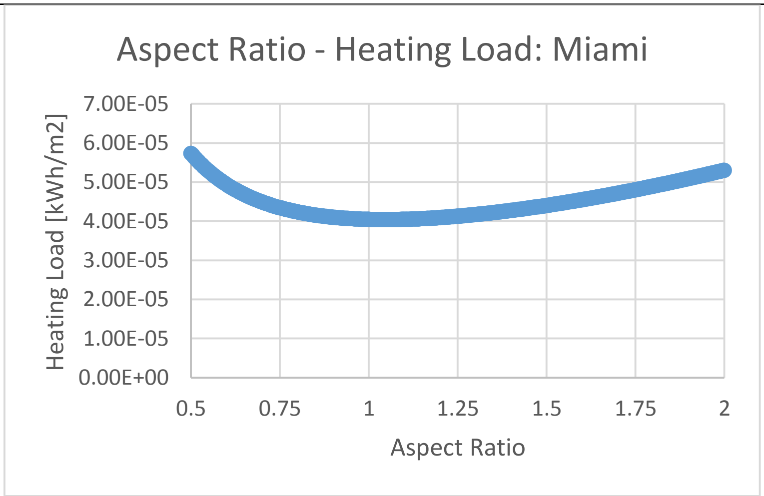
For future studies, the comparison between using a white roof and additional insulation could be conducted as a trade-off, and determine which is most cost-beneficial as there is little advantage to gain in northernmost climates.

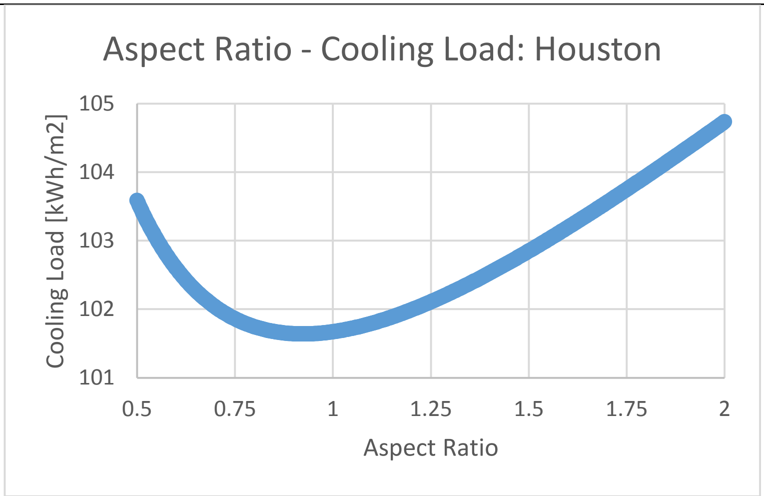
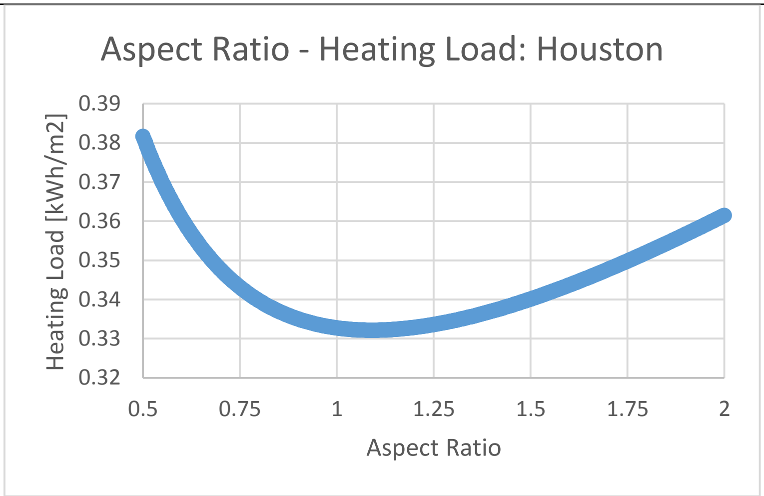
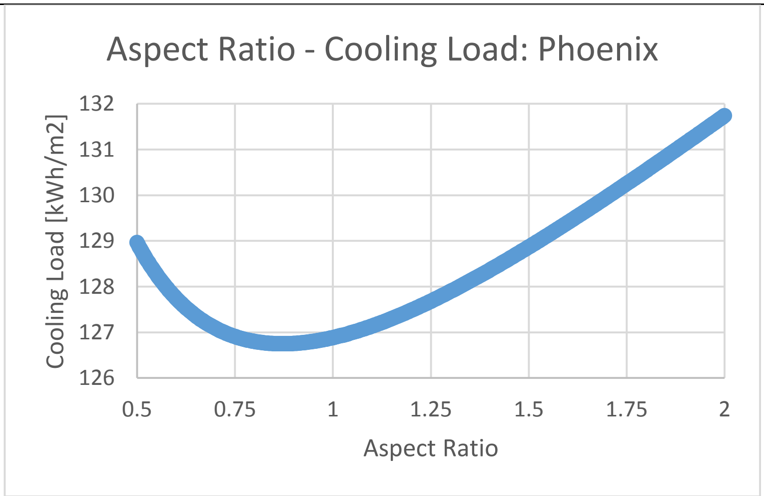
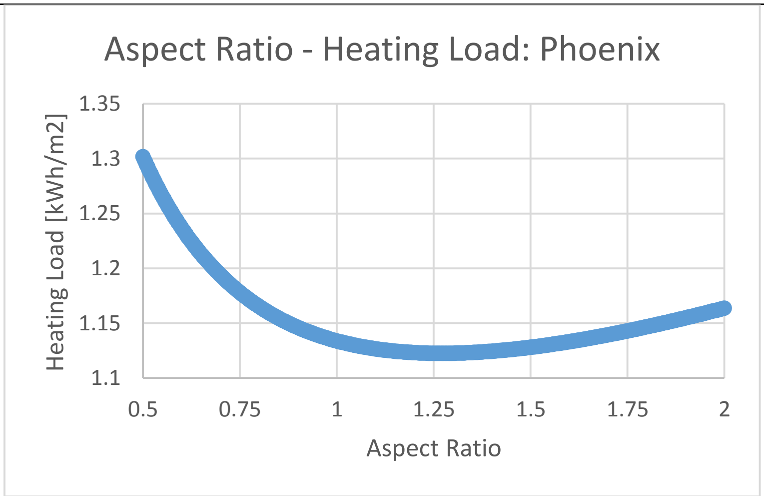
The effects of cool roofs on residential buildings is another aspect that could be explored in future studies, as the parametric analyses in this study is based on a commercial prototype building.

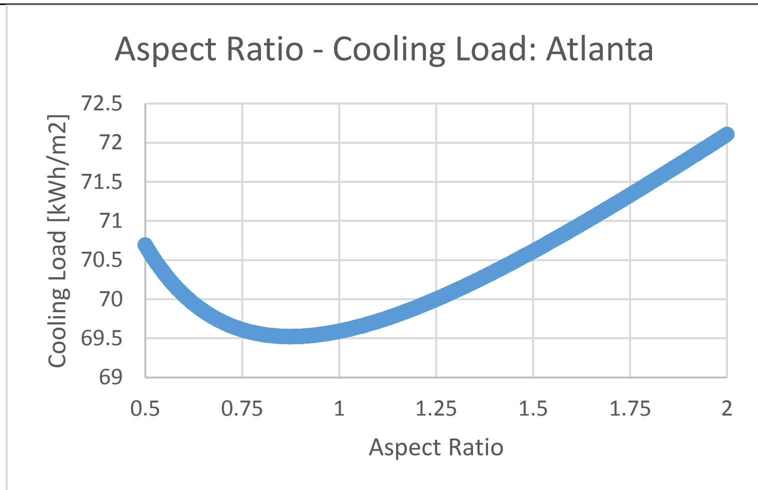
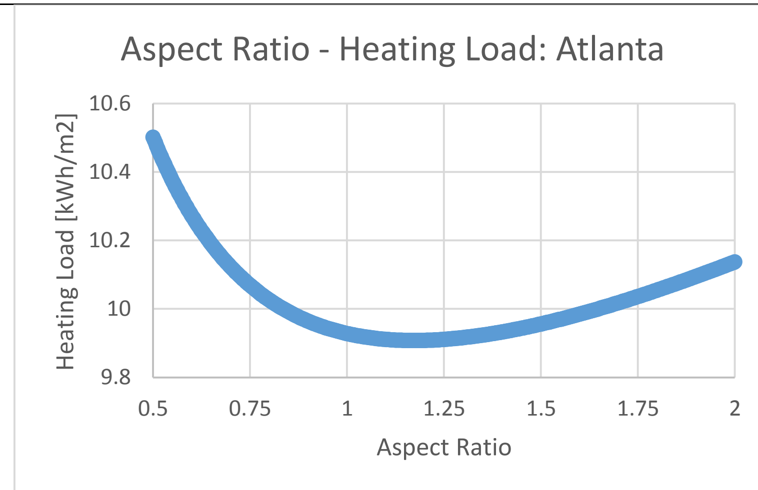
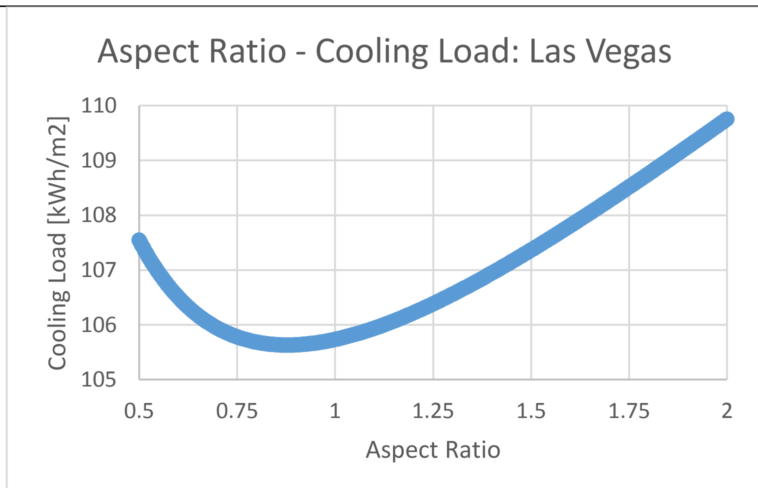
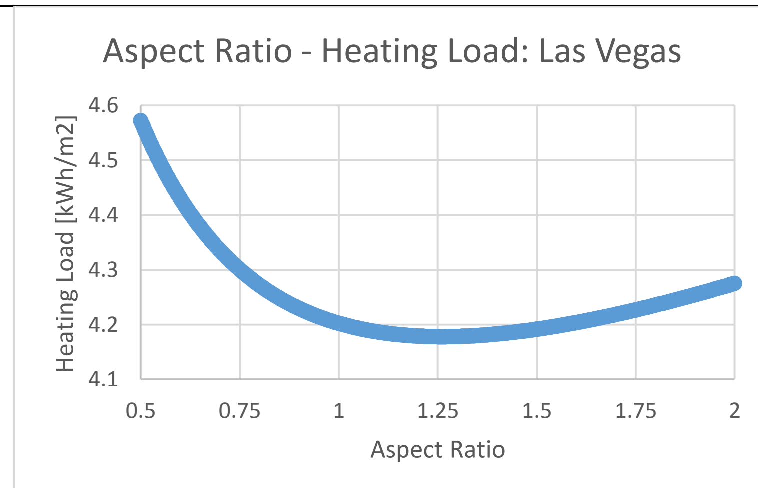
APPENDIX A

PARAMETRIC PLOTS AND GRAPHS

1. Aspect Ratio and Building Loads

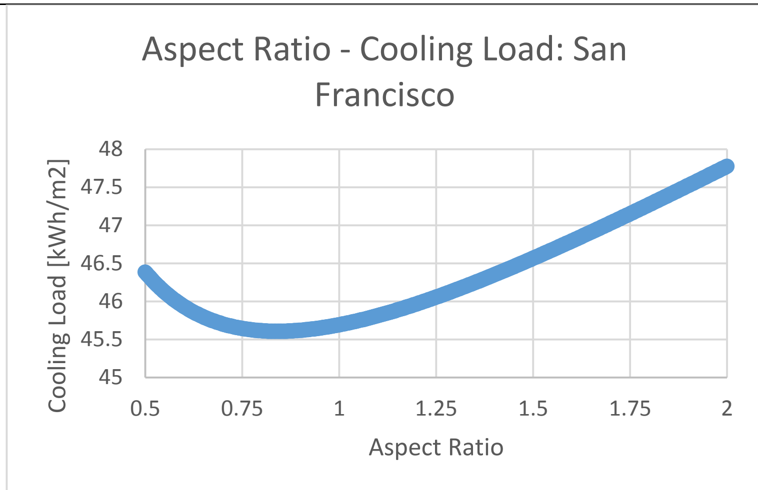
City, Climate Zone	Cooling Loads	Heating Loads
Miami, 1A		

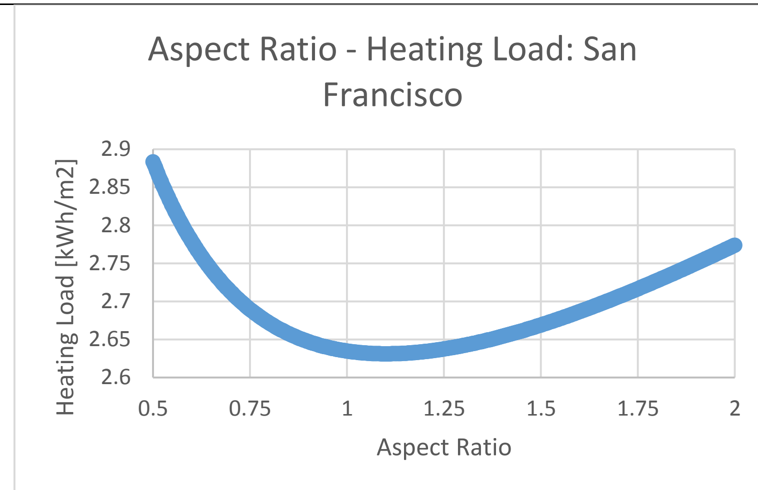
Houston, 2A		
Phoenix, 2B		

Atlanta, 3A		
Las Vegas, 3B		

San Francisco,

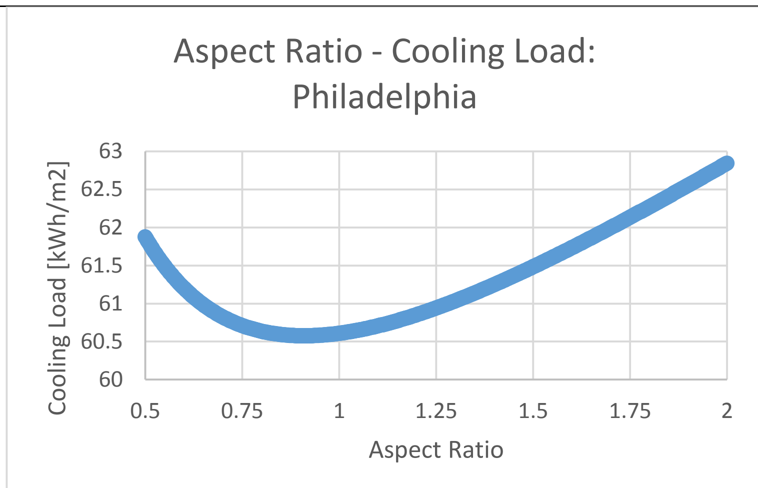
3C

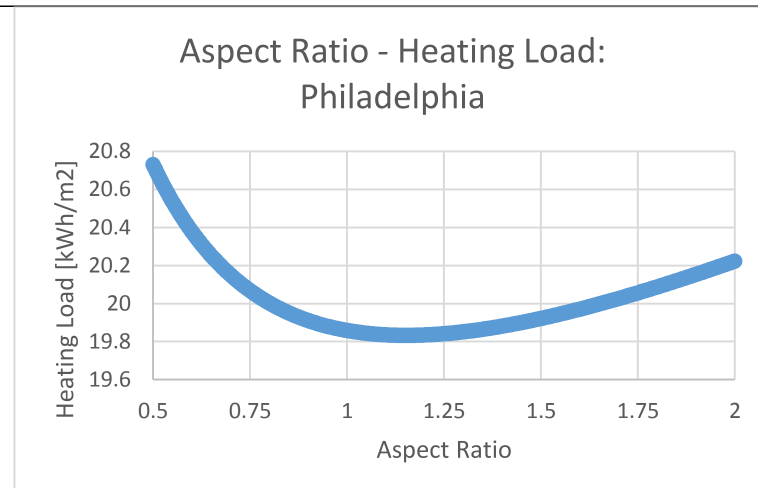




Philadelphia,

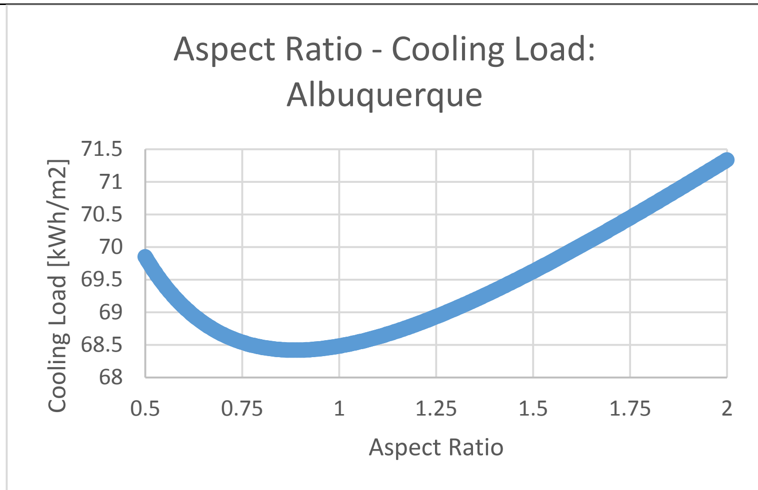
4A

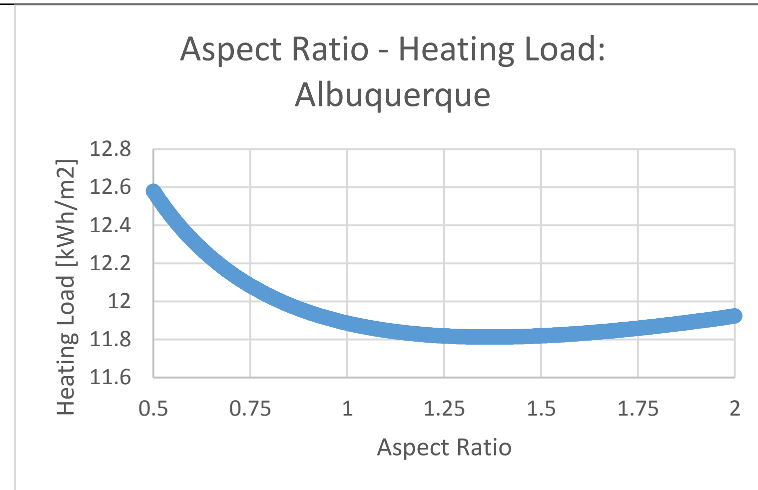




Albuquerque,

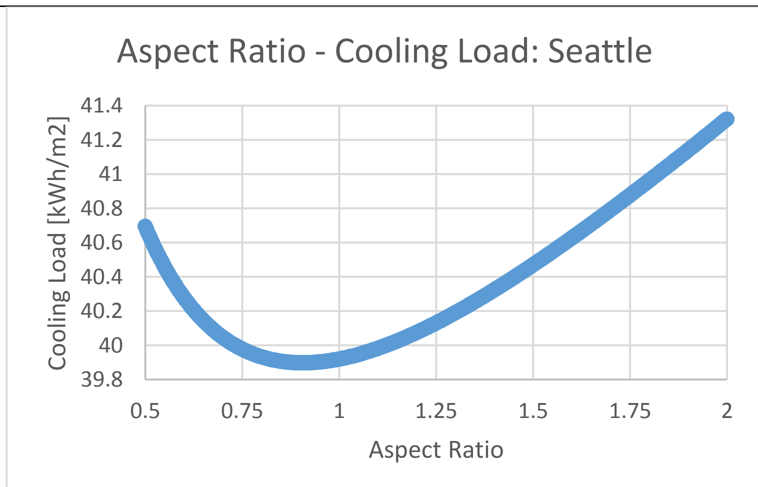
4B

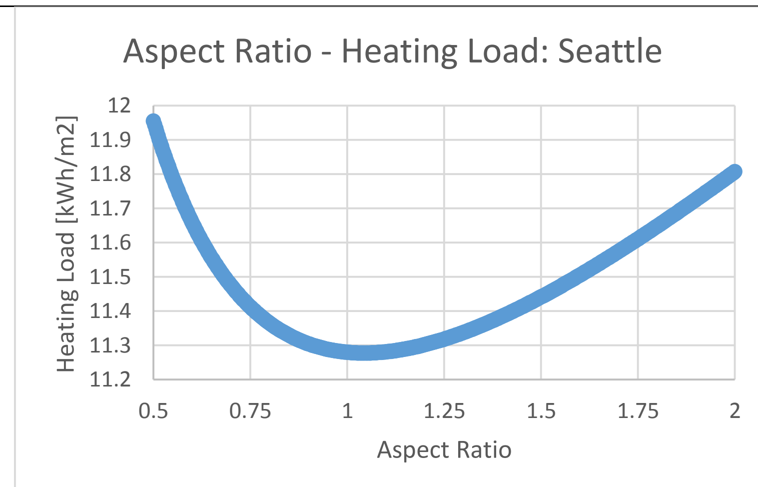




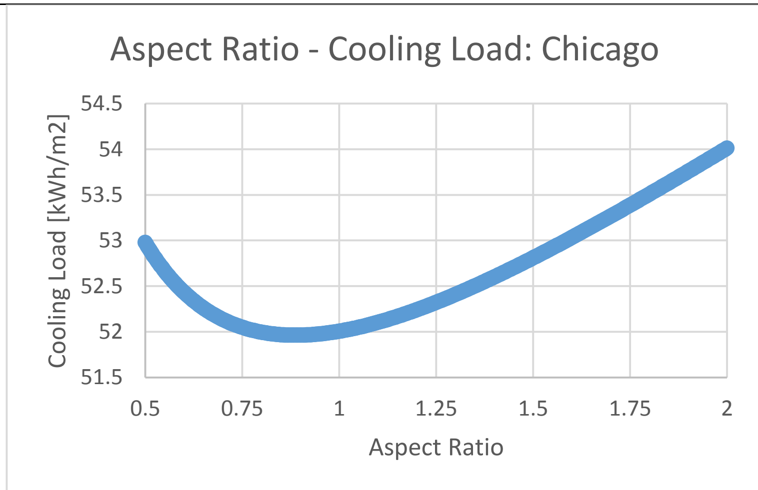
Seattle,

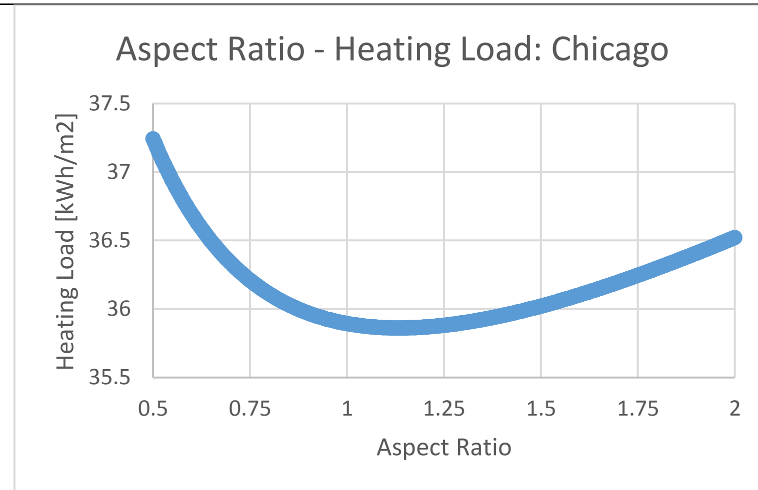
4C



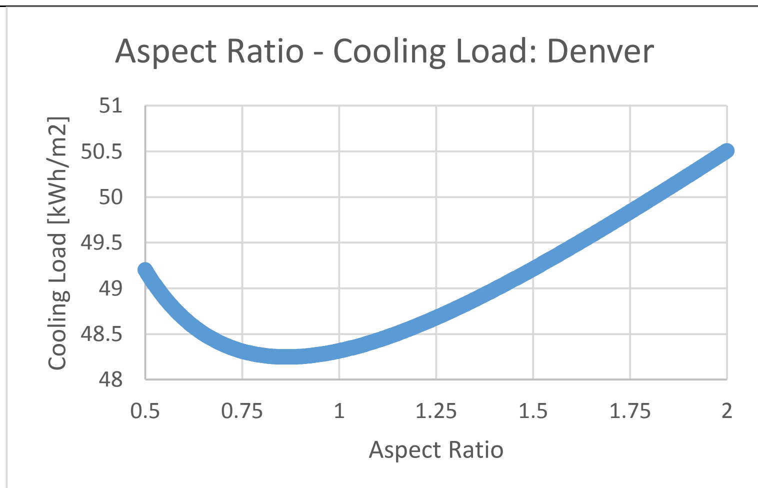


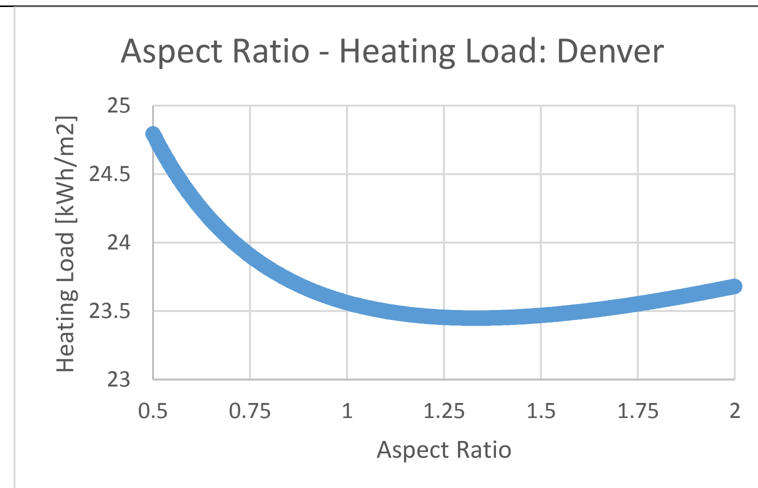
Chicago, 5A





Denver, 5B





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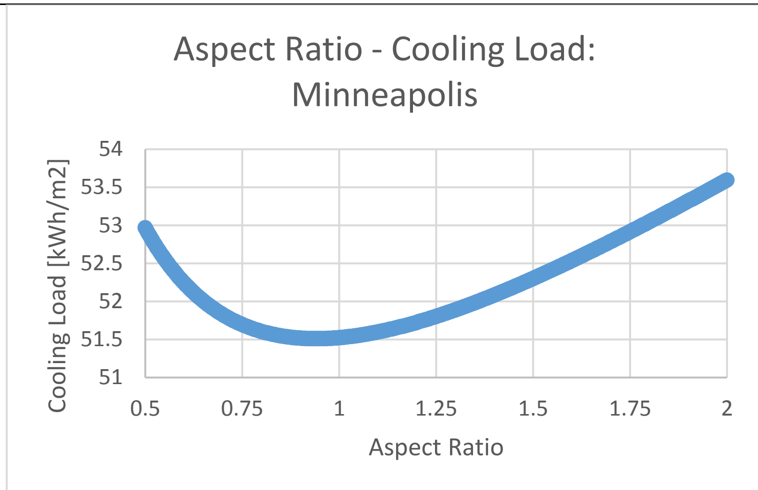
<td>
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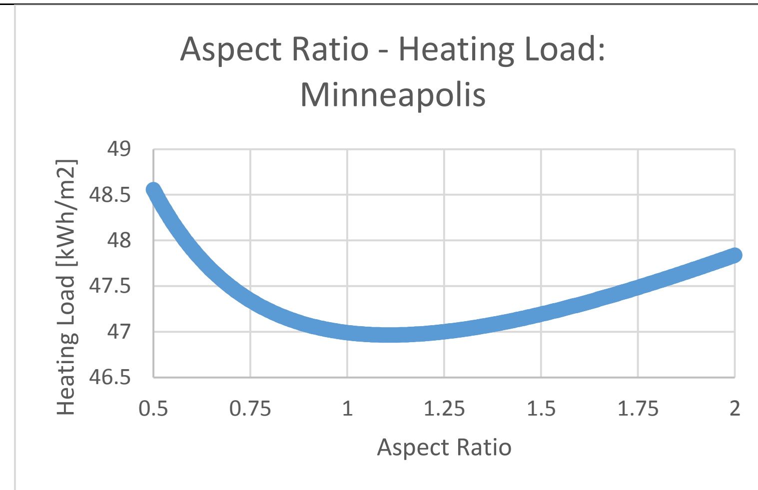
<td>
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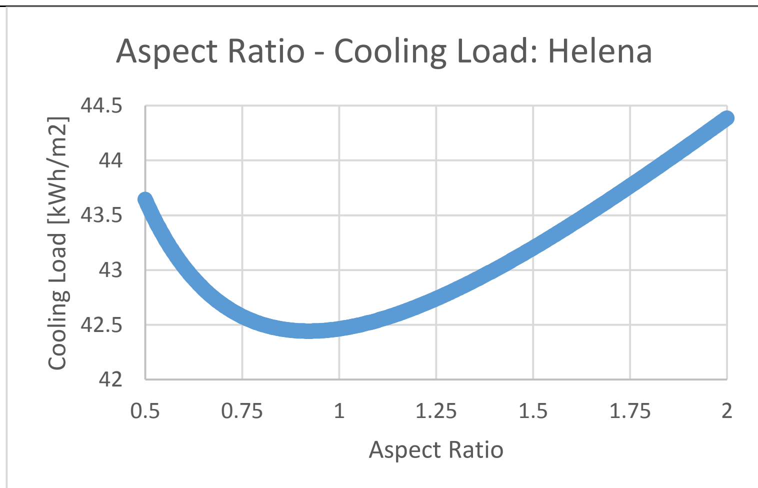
<td>
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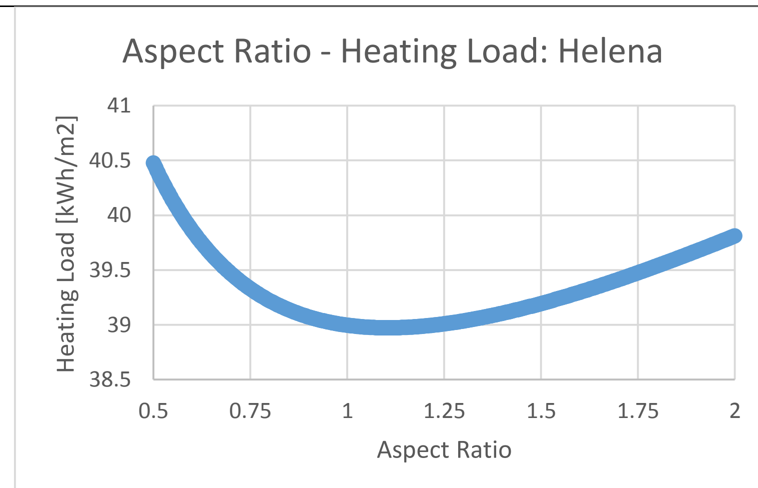
<td>
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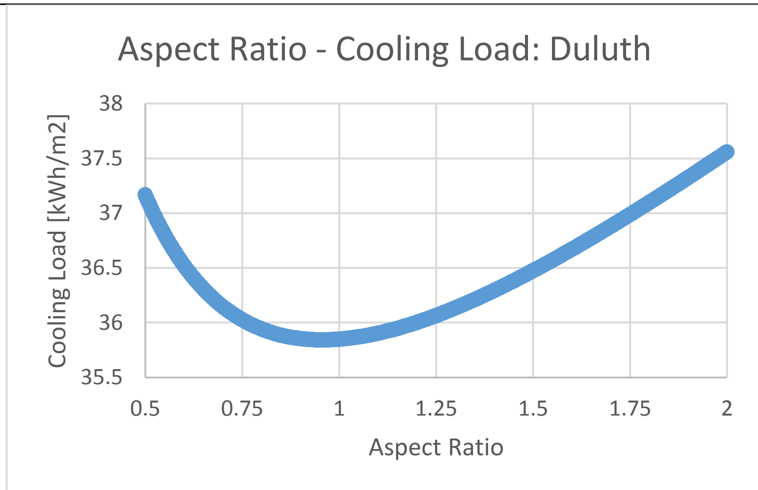
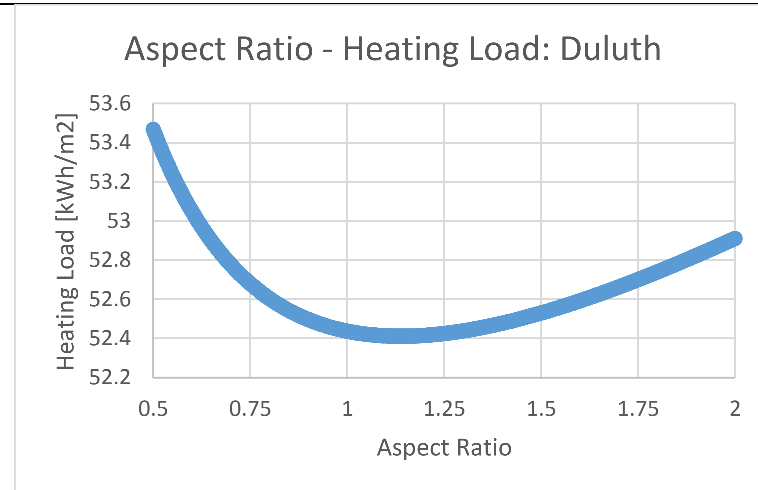
7</td><td>
</td><td>
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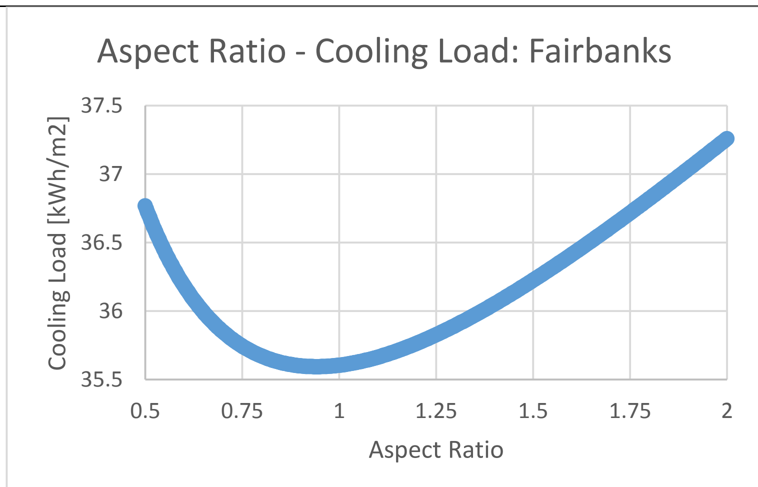
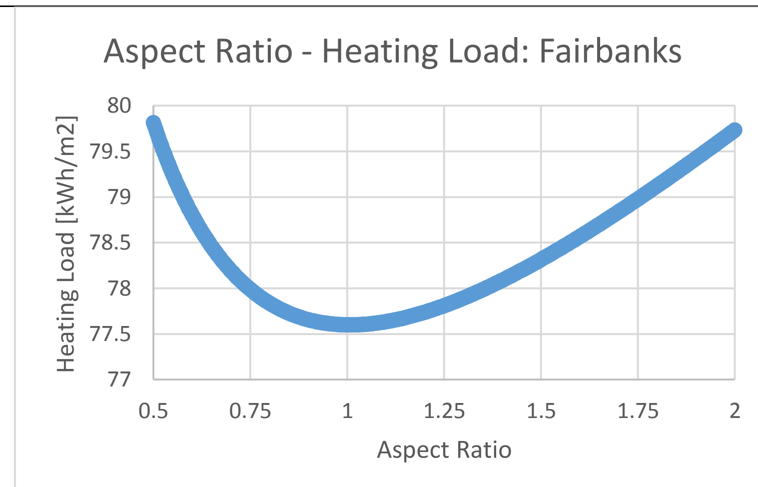
8</td><td>
</td><td>
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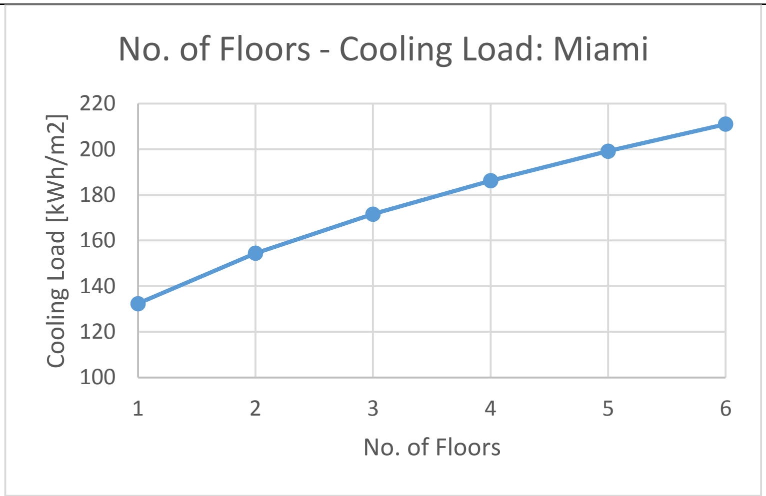
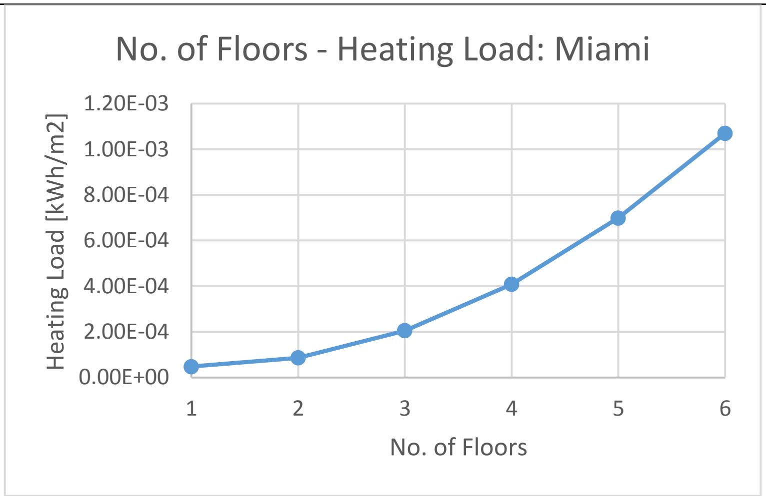
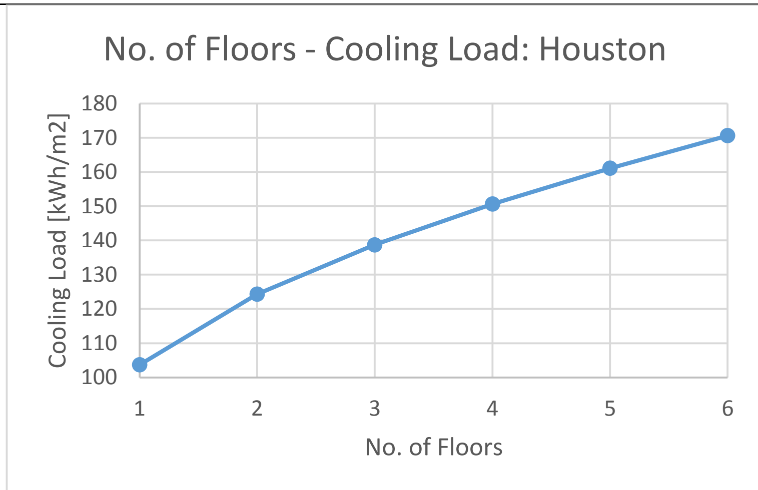
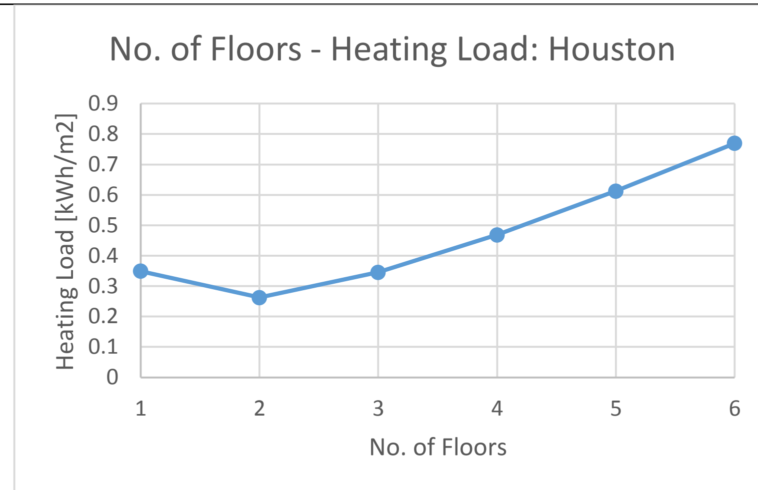
2. No. of Floors and Building Loads

City, Climate Zone	Cooling Loads	Heating Loads
Miami, 1A		

Houston,

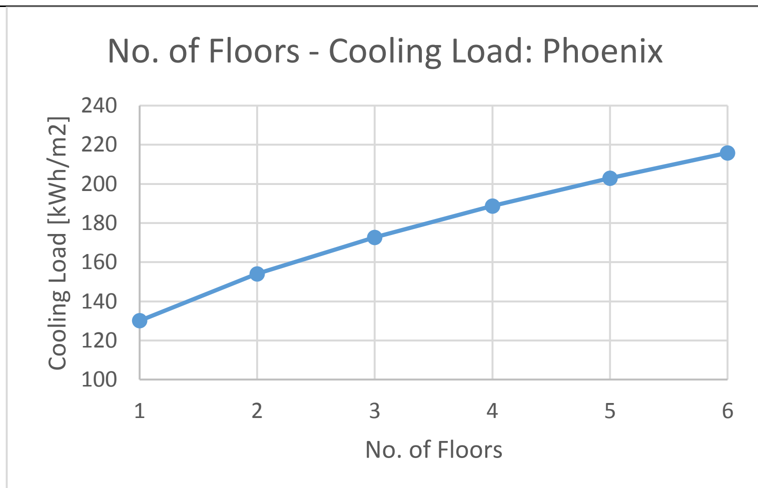
2A

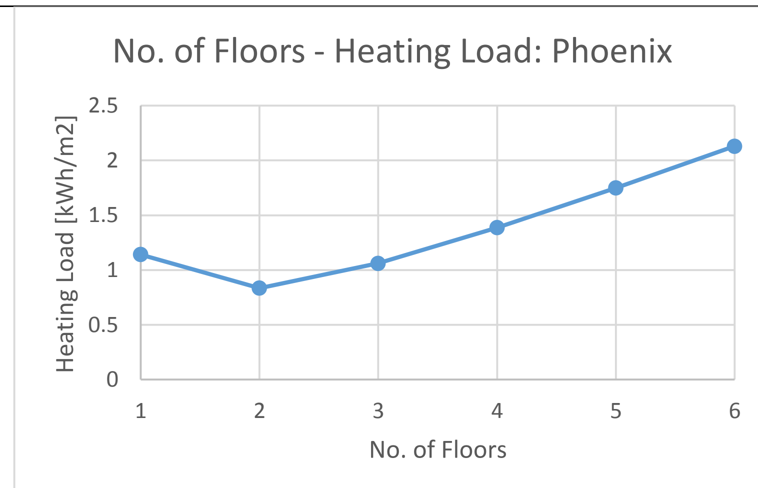




Phoenix,

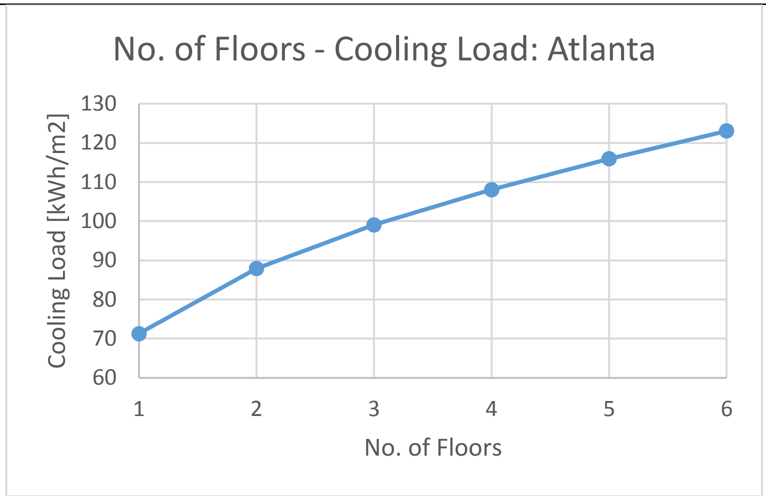
2B

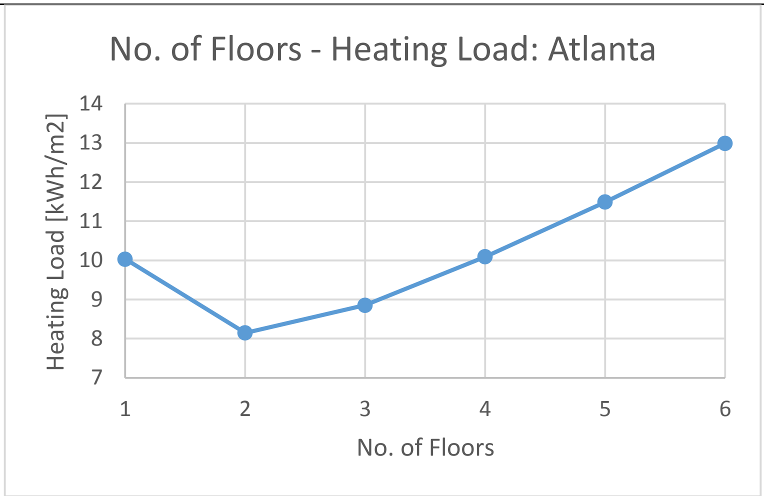




Atlanta,

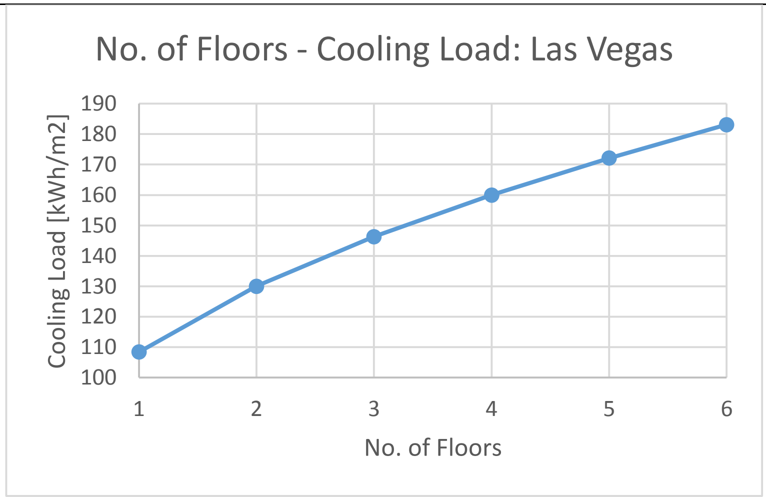
3A

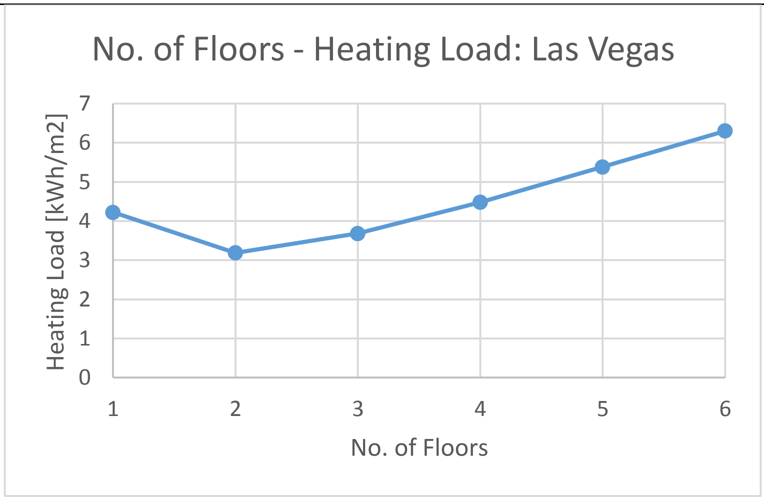




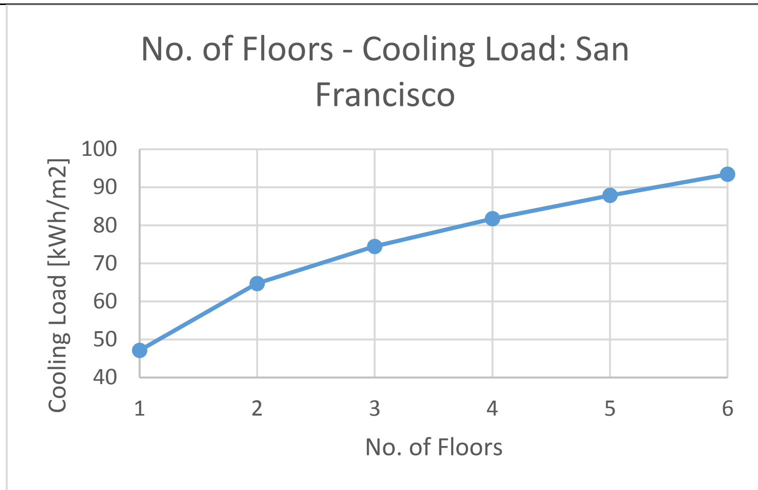
Las Vegas,

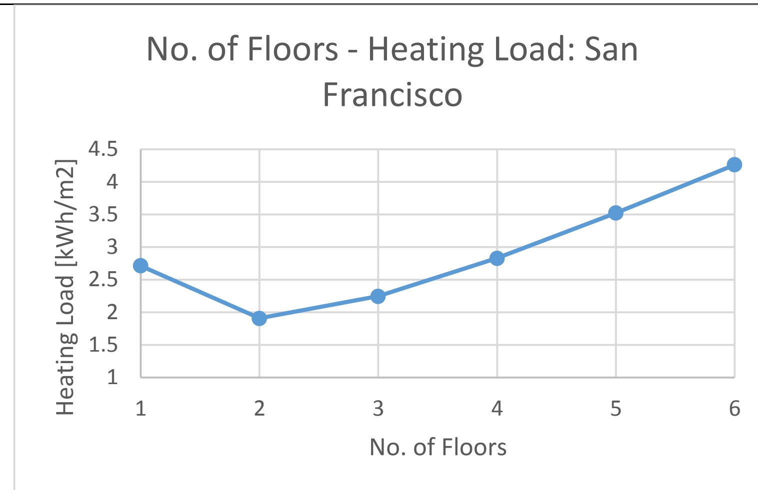
3B



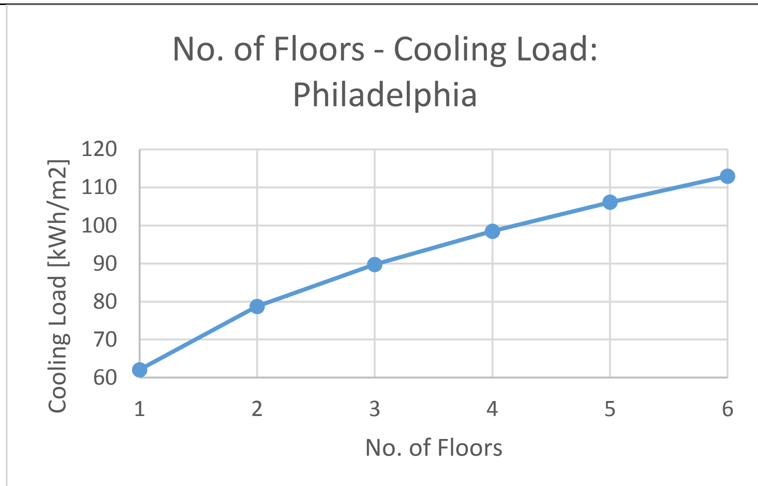


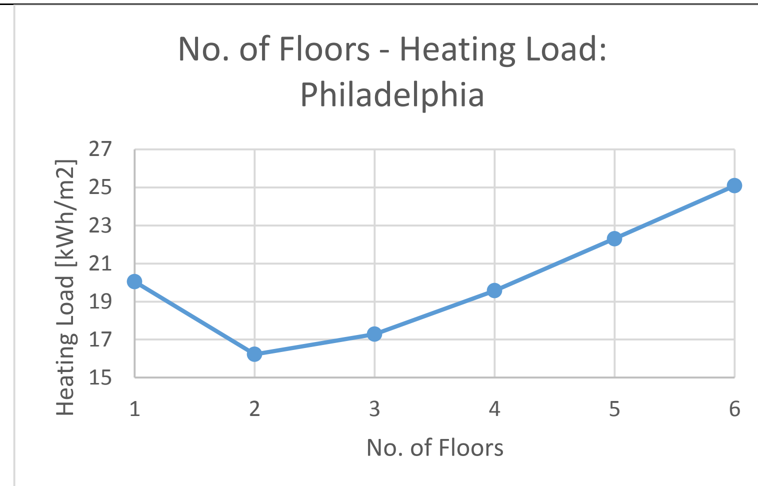
San Francisco, 3C

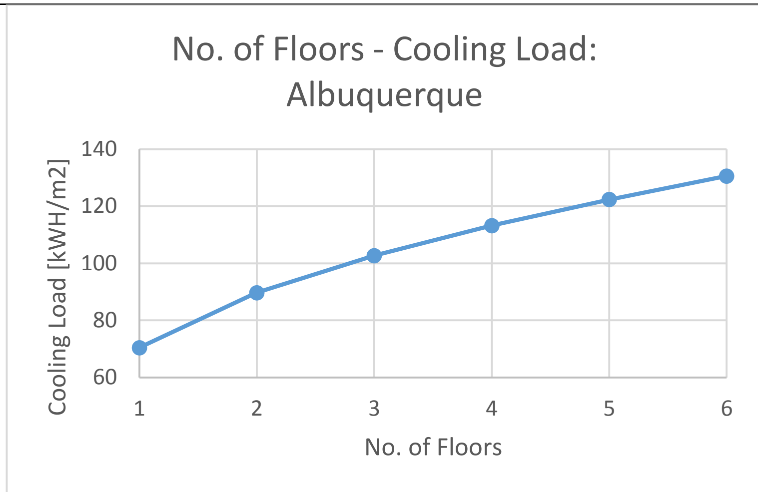
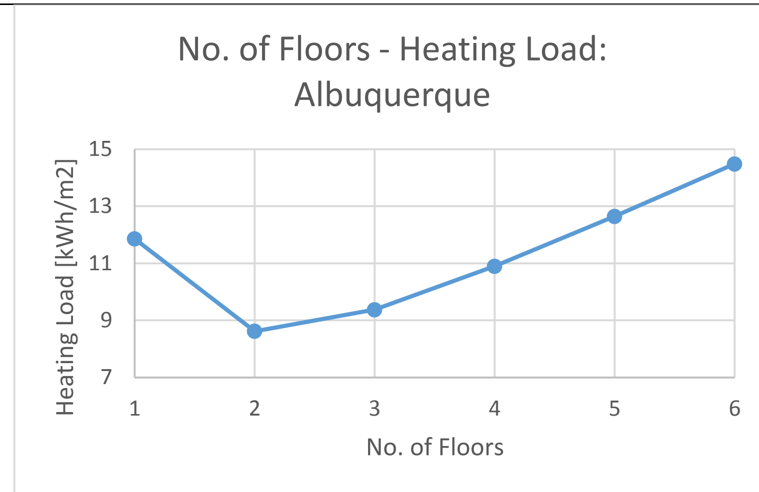
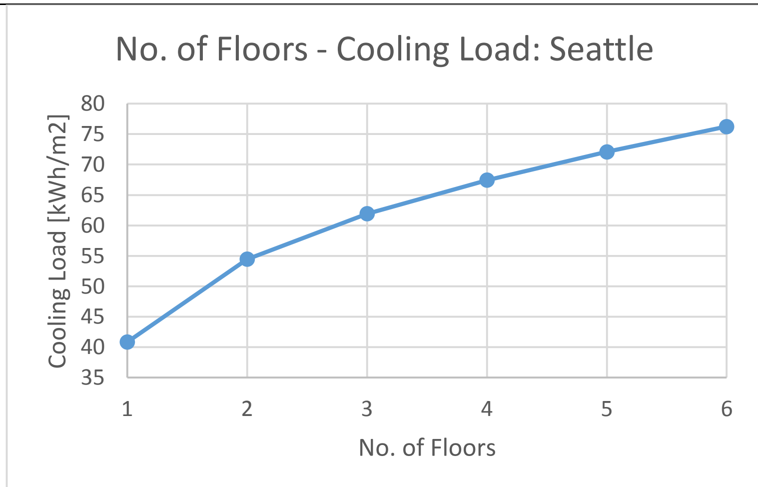
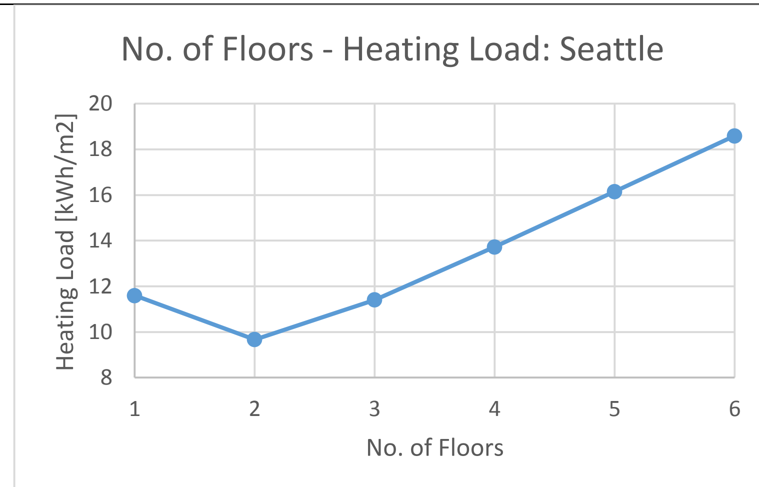




Philadelphia, 4A

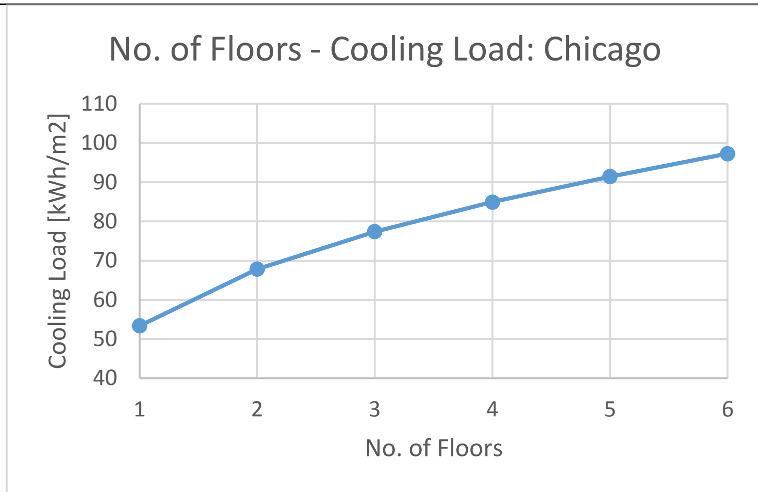


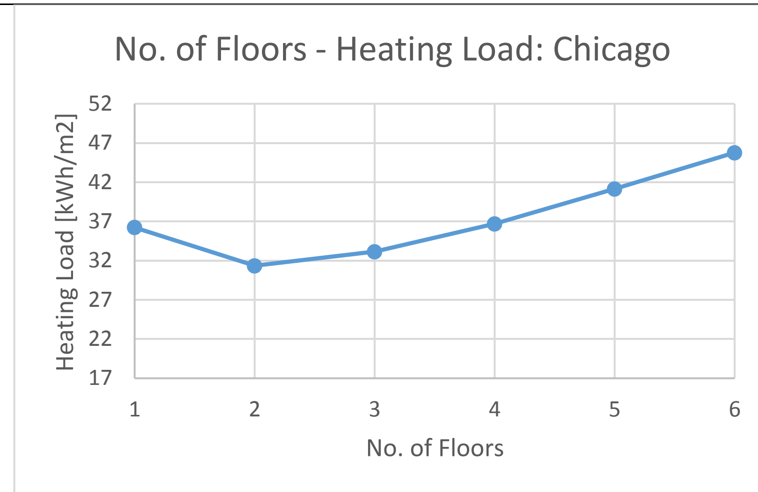


Albuquerque, 4B		
Seattle, 4C		

Chicago,

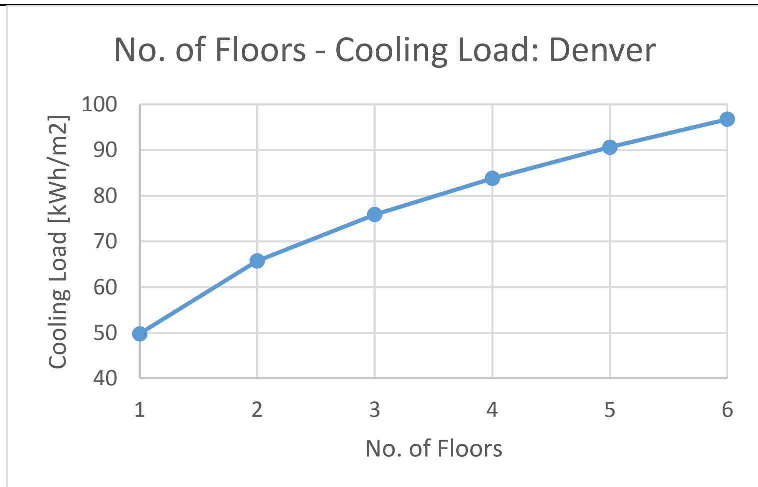
5A

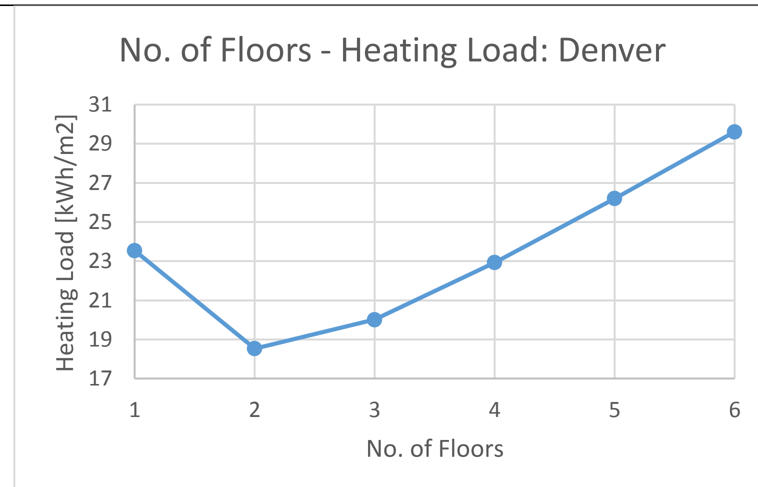




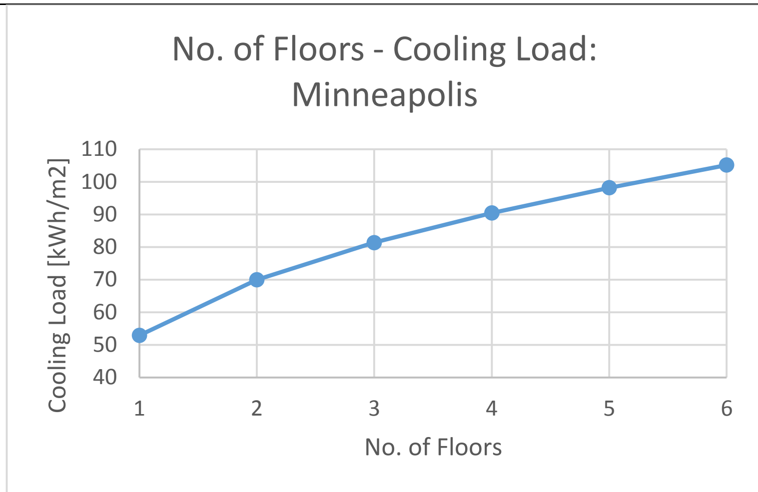
Denver,

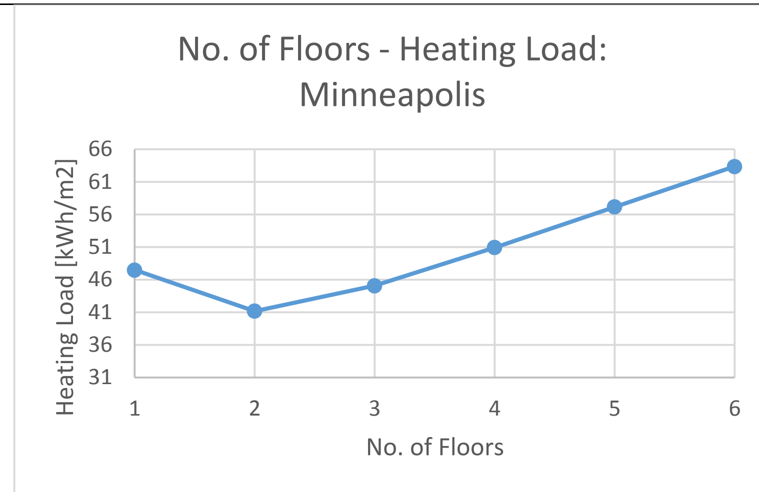
5B



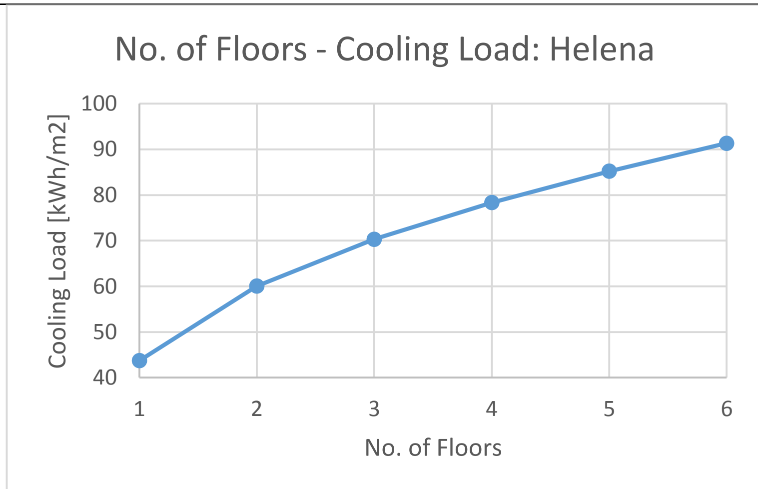


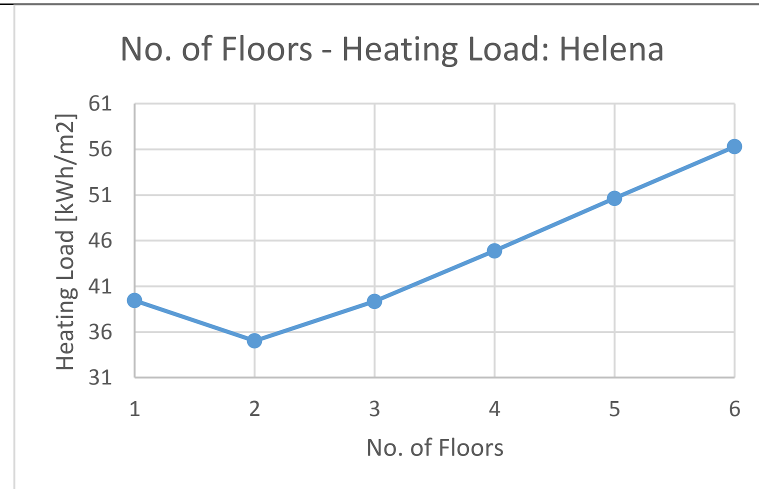
Minneapolis, 6A

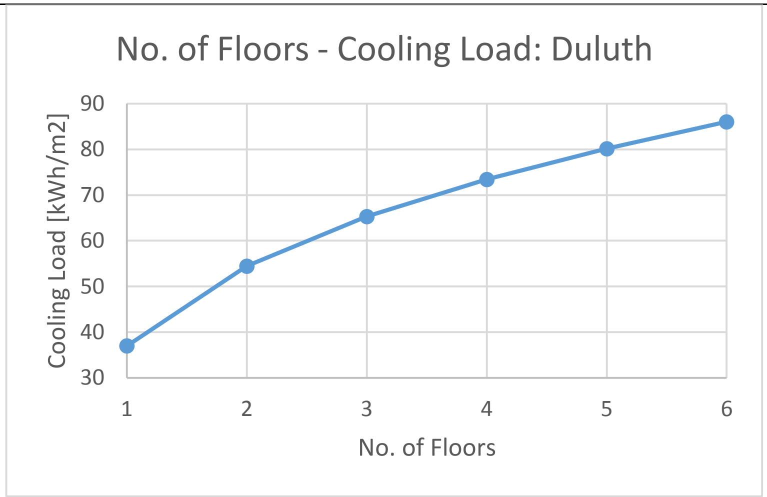
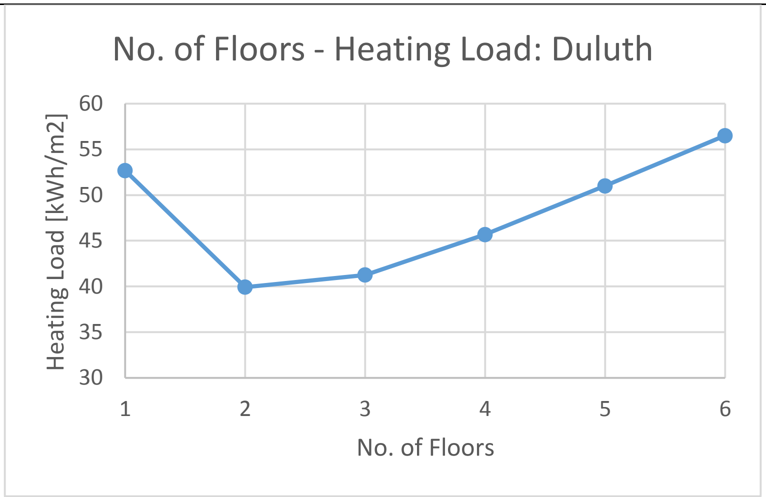
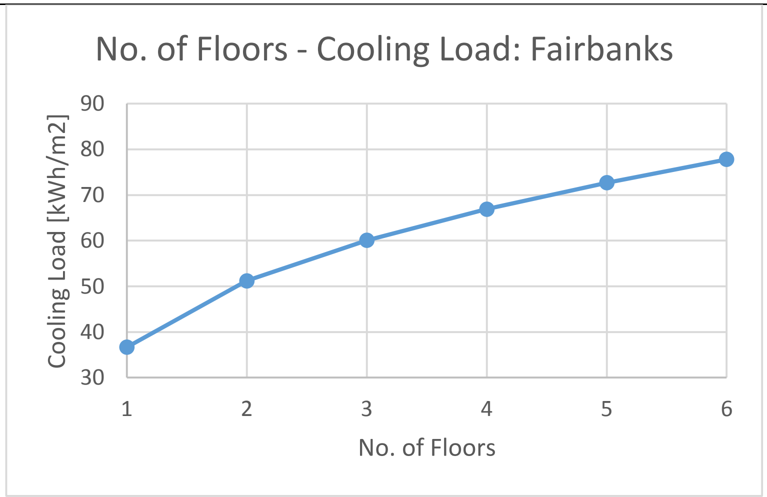
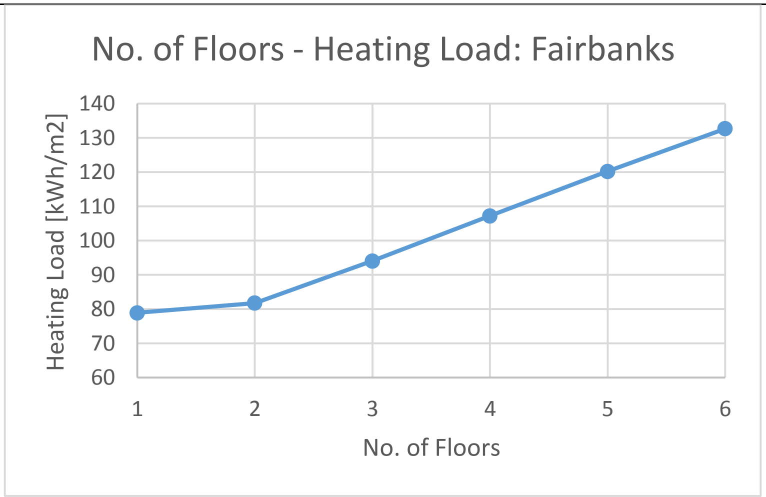




Helena, 6B

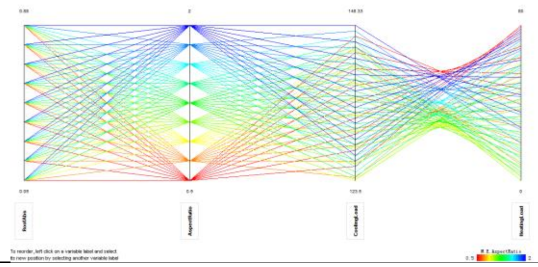
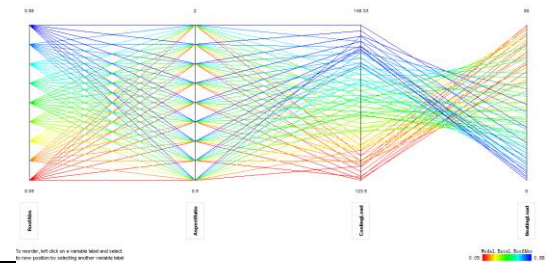
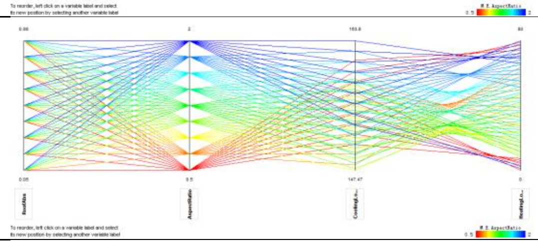
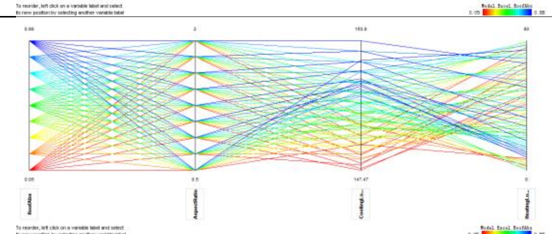
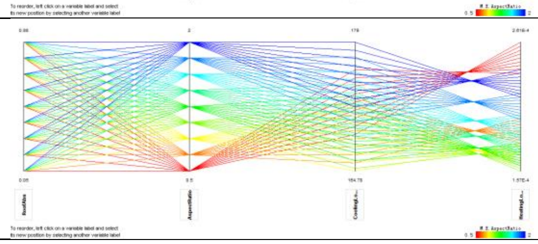
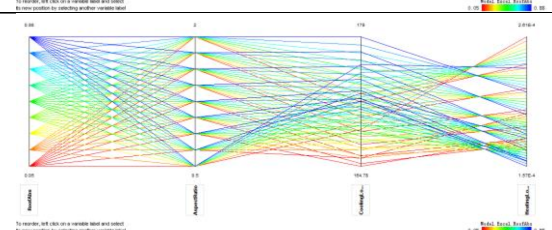
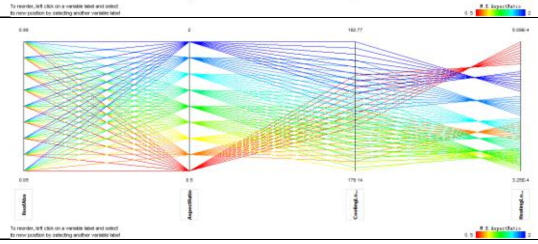
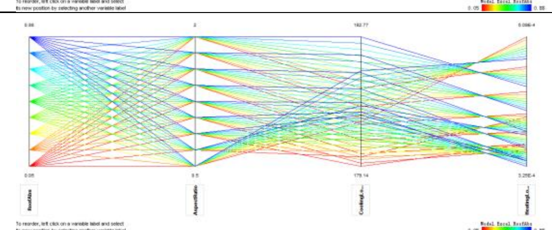
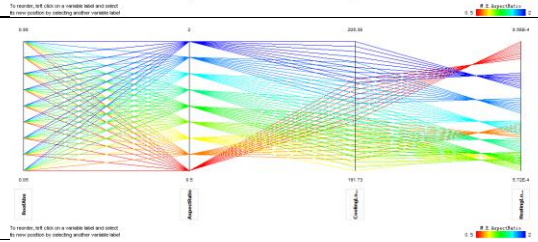
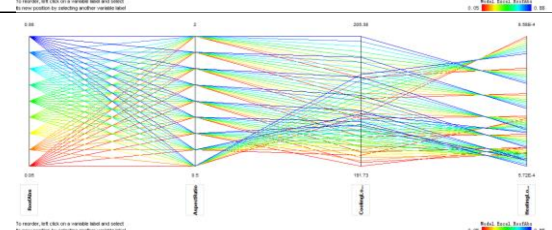
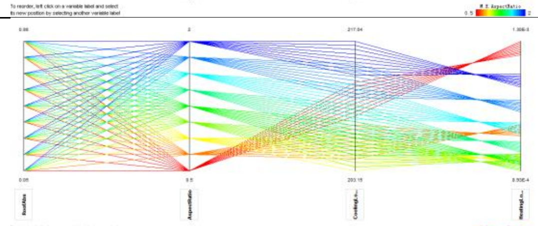
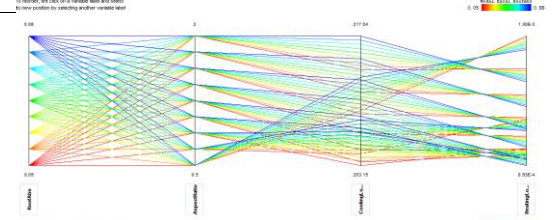




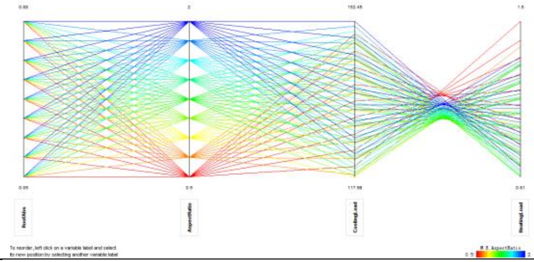
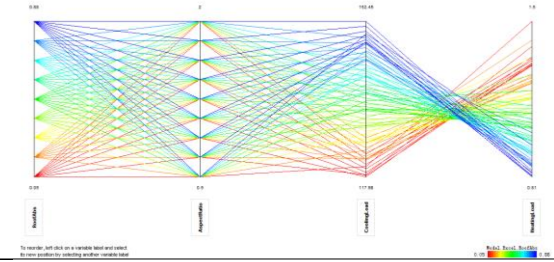
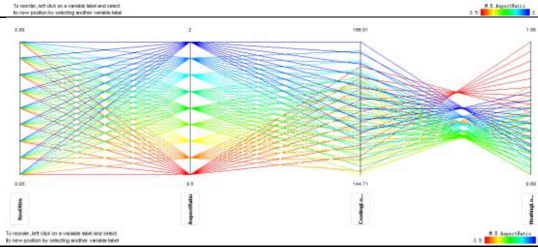
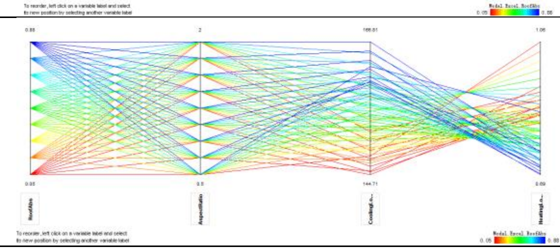
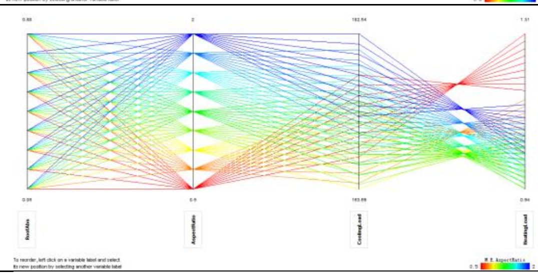
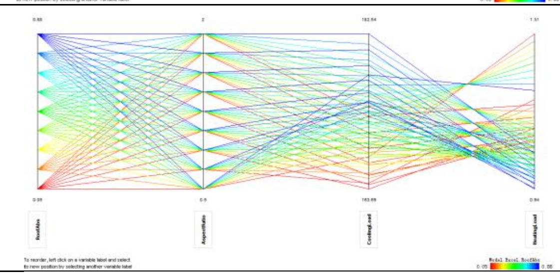
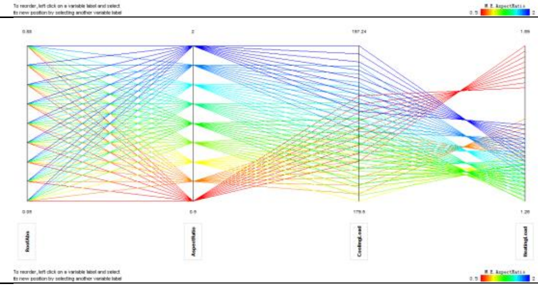
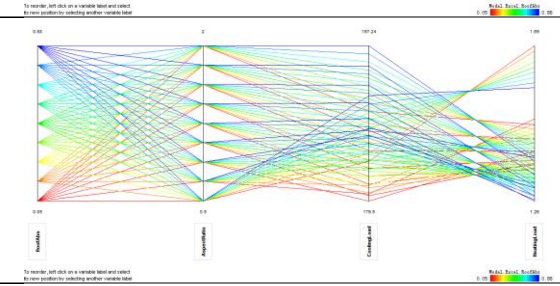
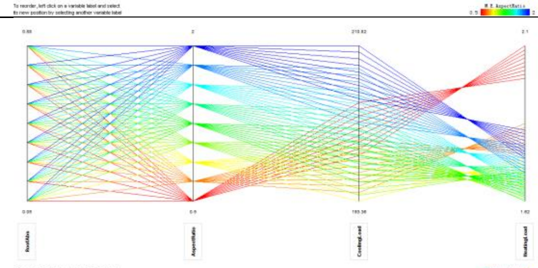
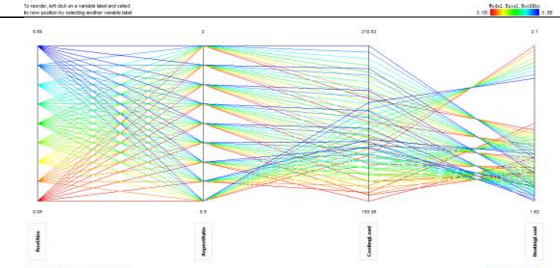
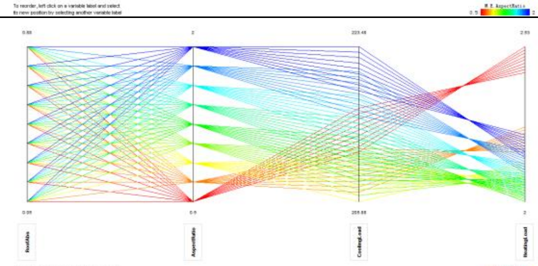
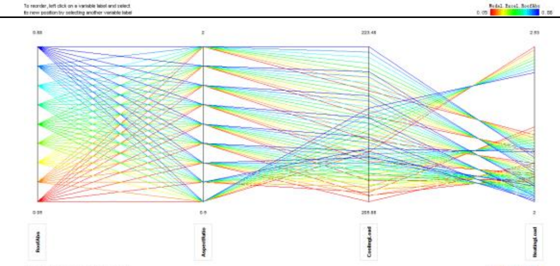
Duluth, 7		
Fairbanks, 8		

3. Parallel Coordinates Plots

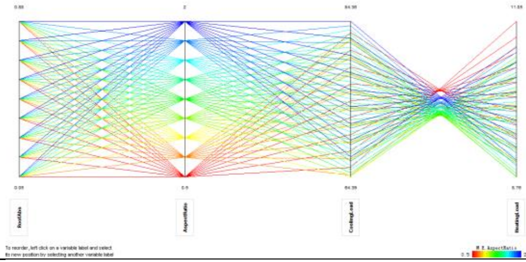
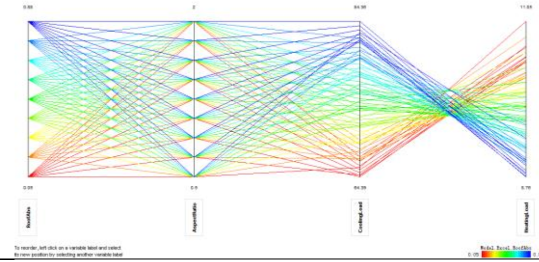
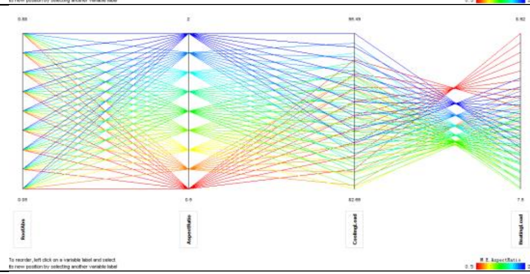
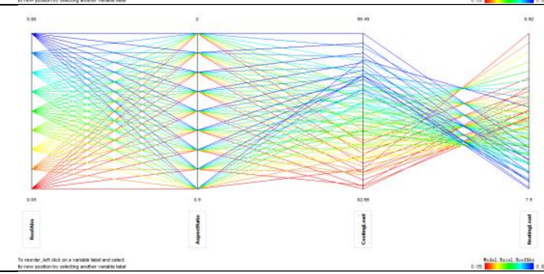
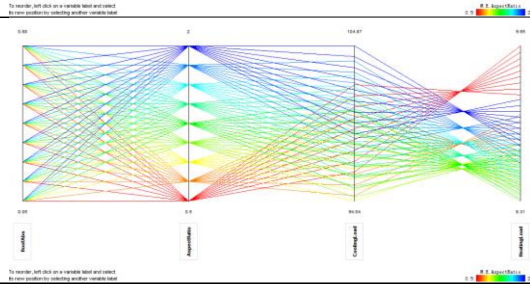
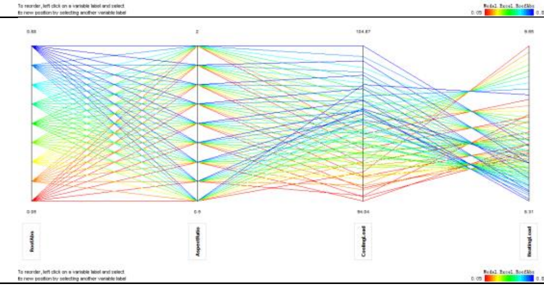
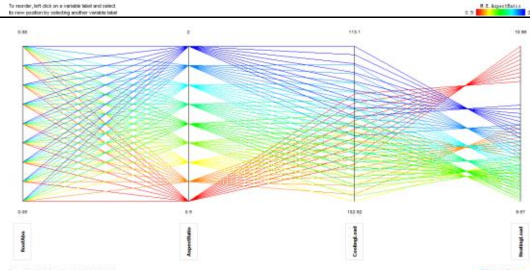
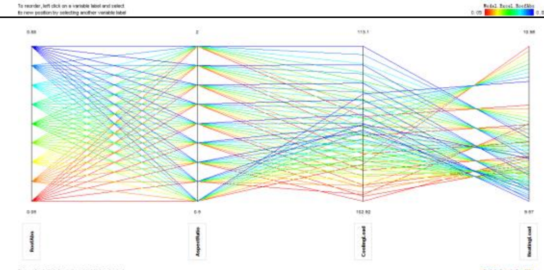
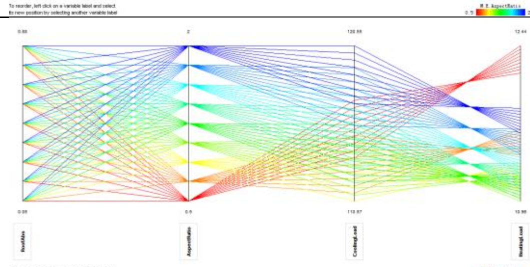
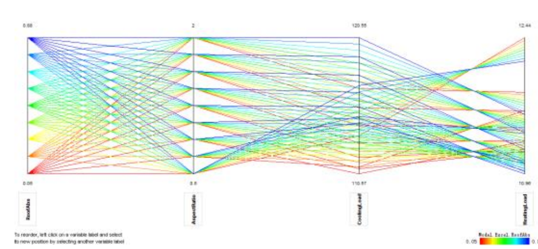
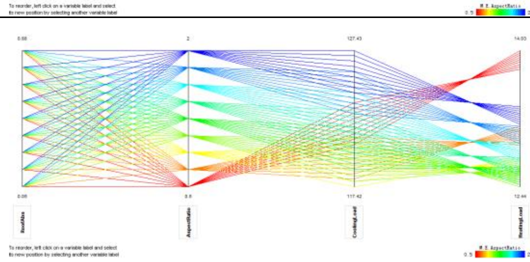
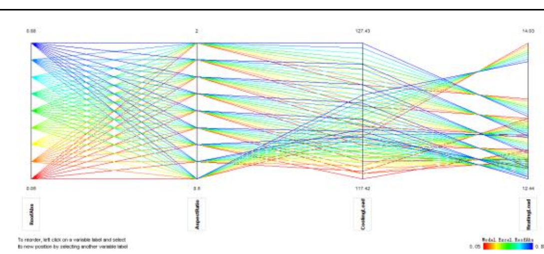
Miami Climate Zone 1A

No. of Floors	Lines colored by Aspect Ratio Aspect Ratio Range [0.5-2]	Lines colored by Roof Absorptance Coefficient Roof Abs. Coefficient Range [0.05-0.88]
1		
2		
3		
4		
5		
6		

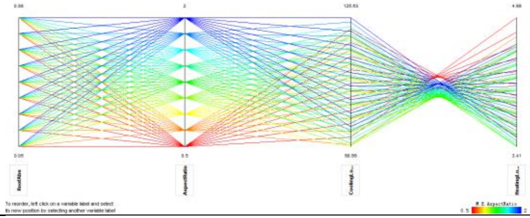
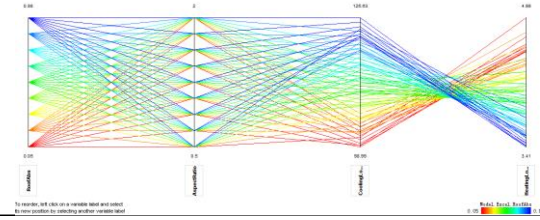
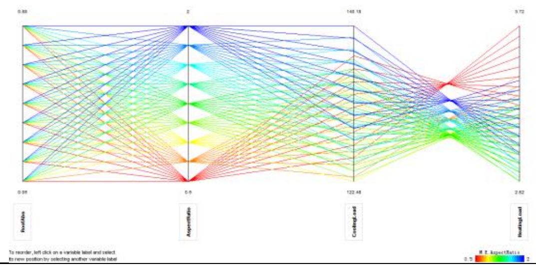
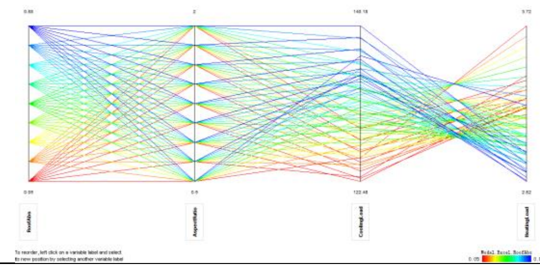
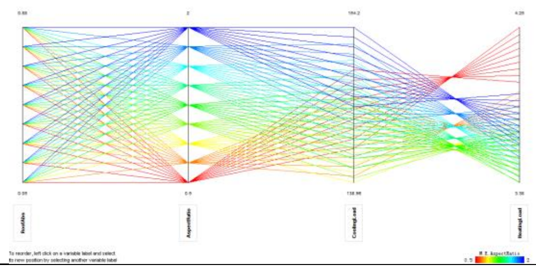
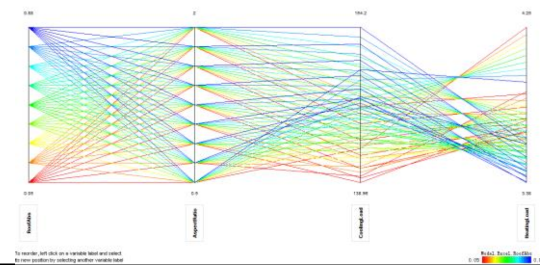
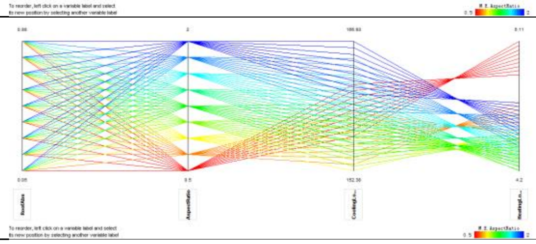
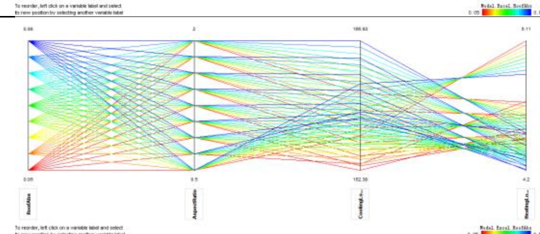
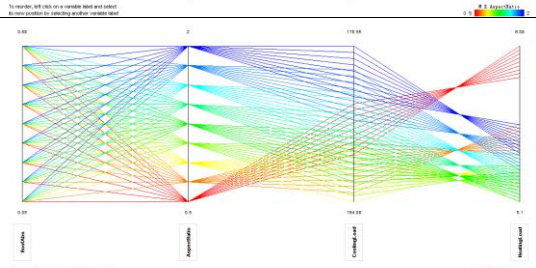
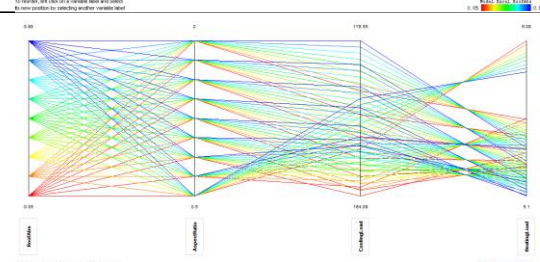
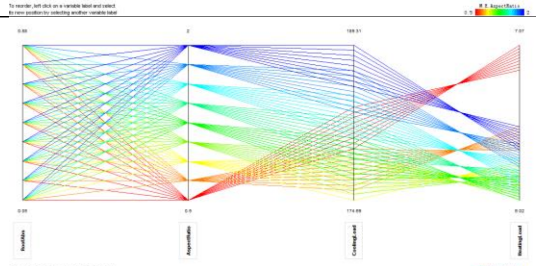
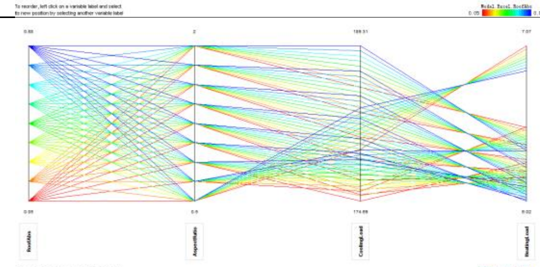
Phoenix Climate Zone 2B

No. of Floors	Lines colored by Aspect Ratio Aspect Ratio Range [0.5-2]	Lines colored by Roof Absorptance Coefficient Roof Abs. Coefficient Range [0.05-0.88]
1		
2		
3		
4		
5		
6		

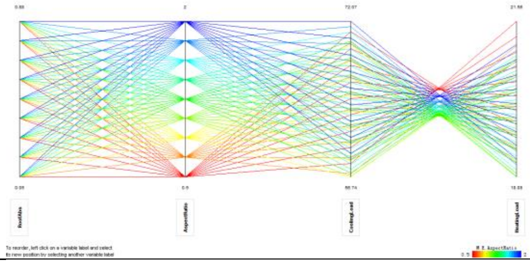
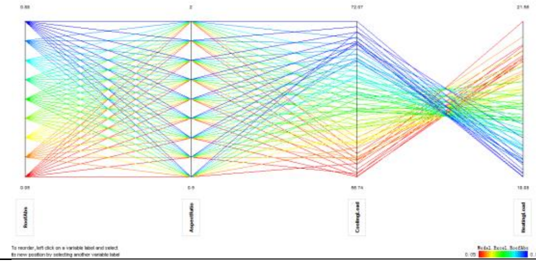
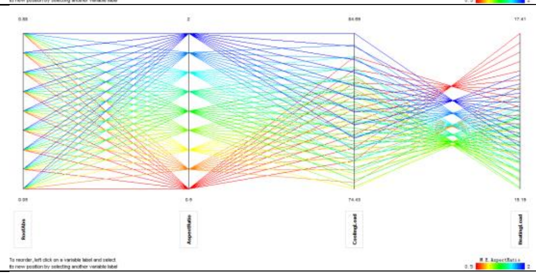
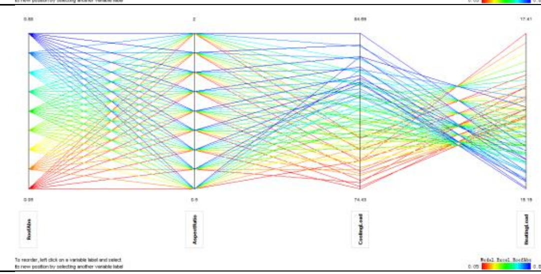
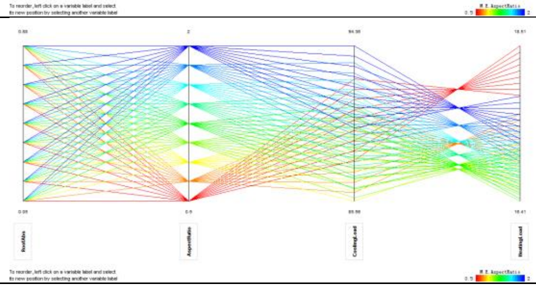
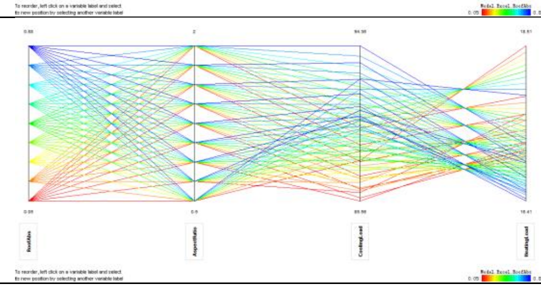
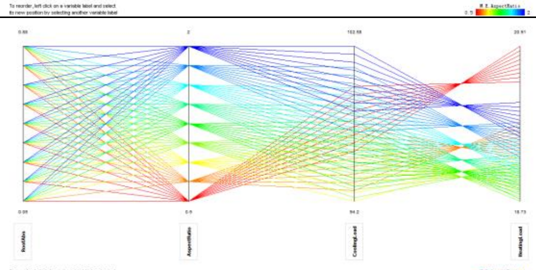
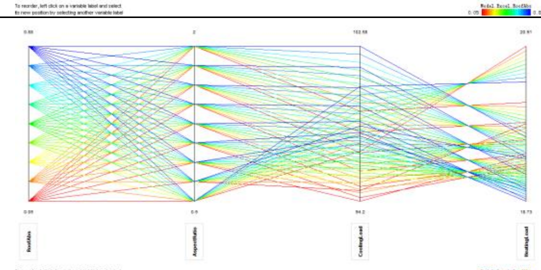
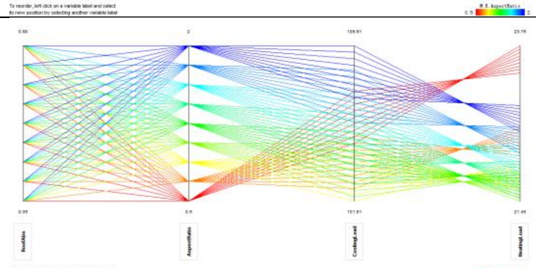
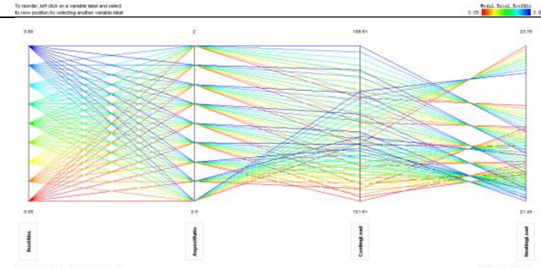
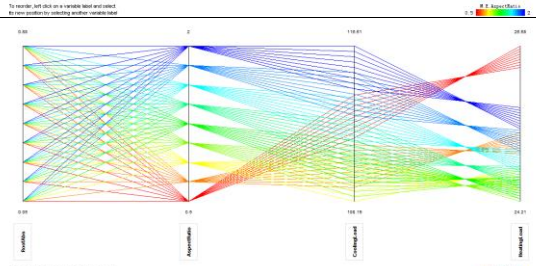
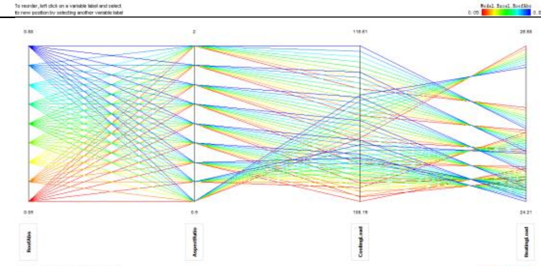
Atlanta Climate Zone 3A

No. of Floors	Lines colored by Aspect Ratio	Lines colored by Roof Absorptance Coefficient
1		
2		
3		
4		
5		
6		

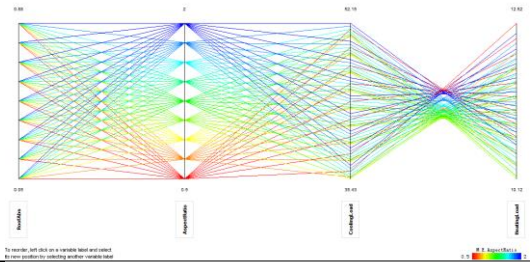
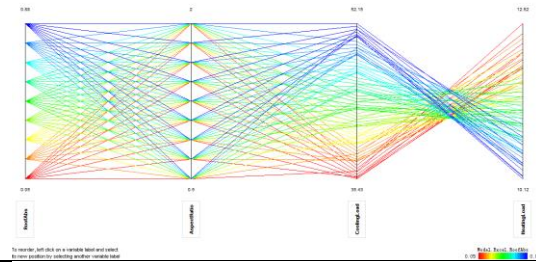
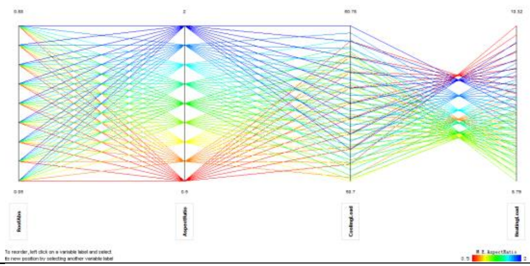
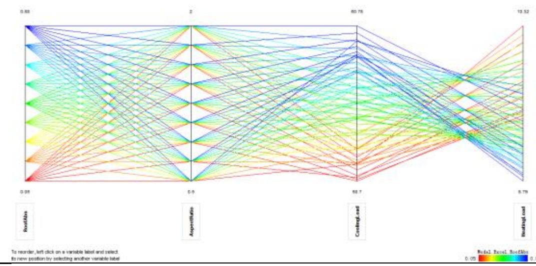
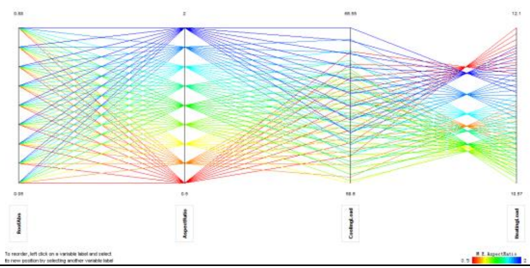
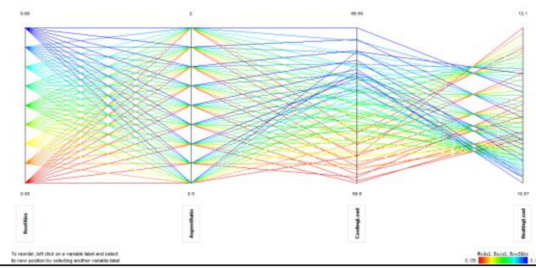
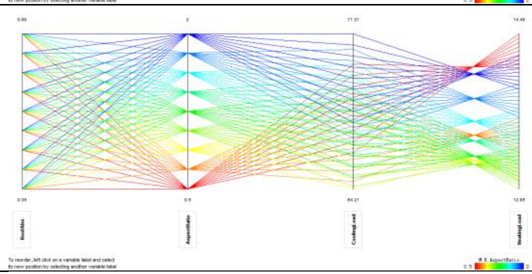
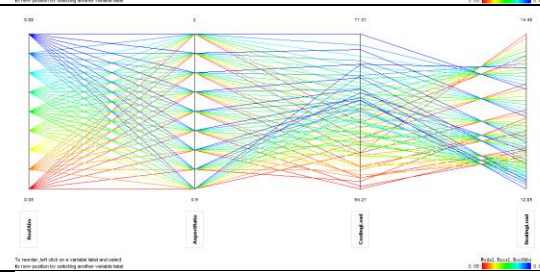
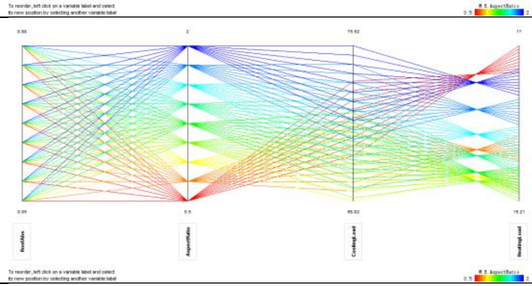
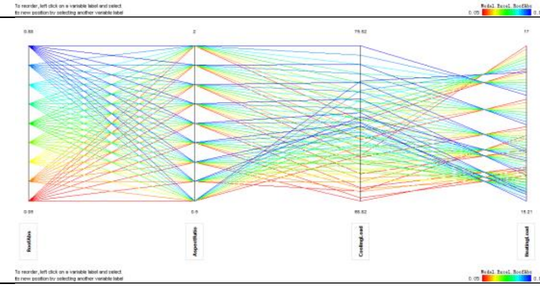
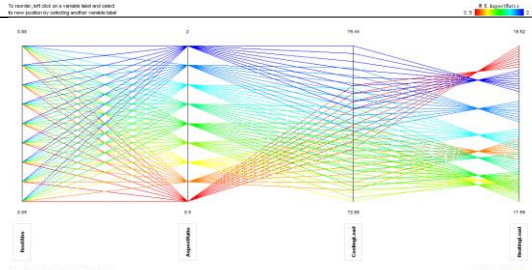
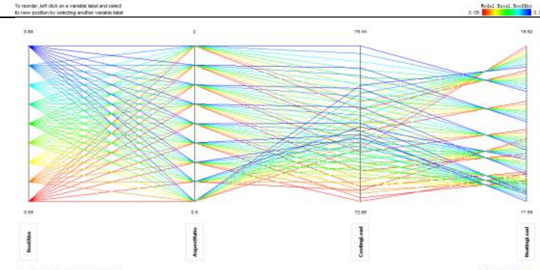
Las Vegas Climate Zone 3B

No. of Floors	Lines colored by Aspect Ratio Aspect Ratio Range [0.5-2]	Lines colored by Roof Absorptance Coefficient Roof Abs. Coefficient Range [0.05-0.88]
1		
2		
3		
4		
5		
6		

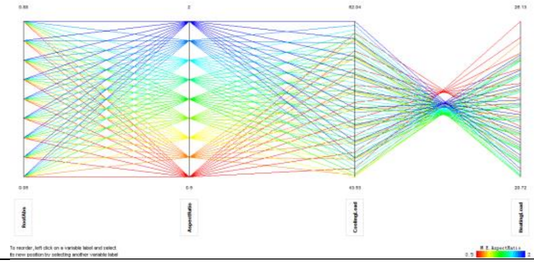
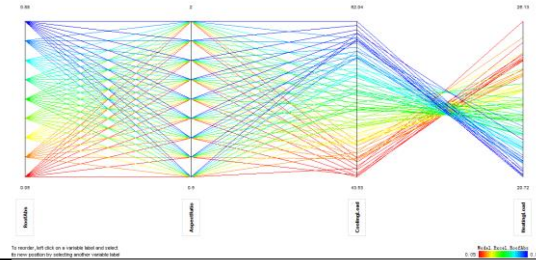
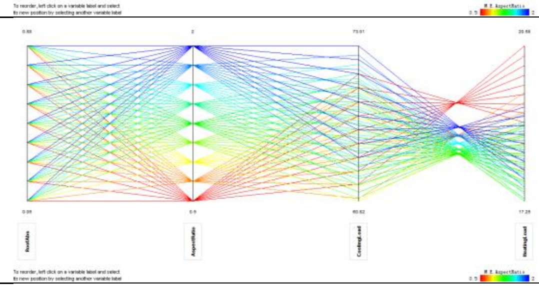
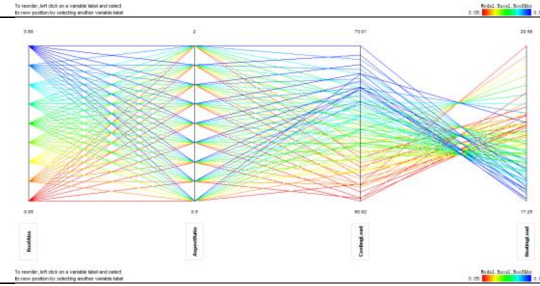
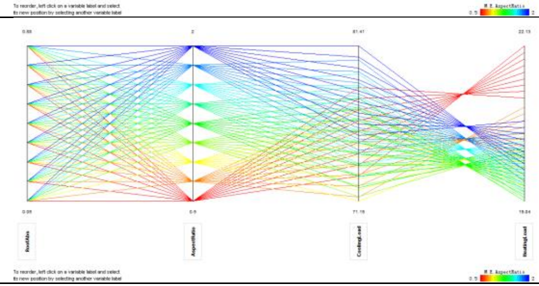
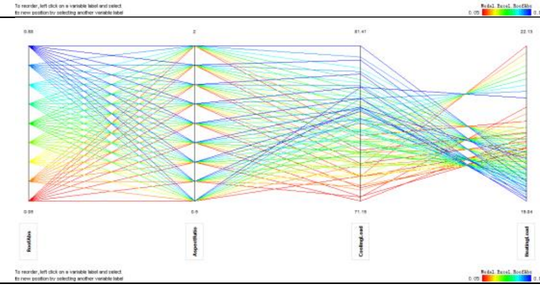
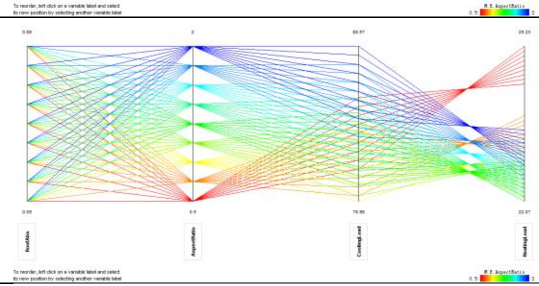
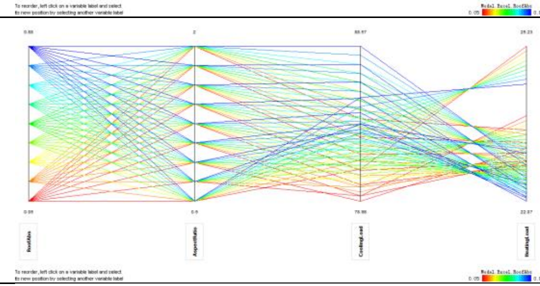
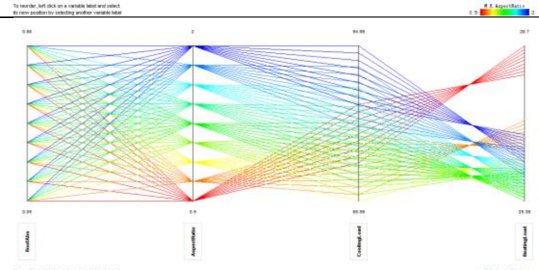
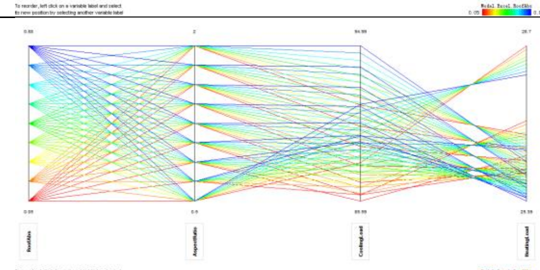
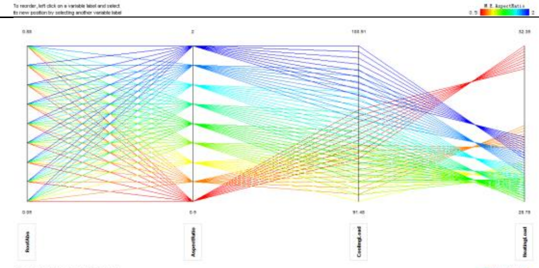
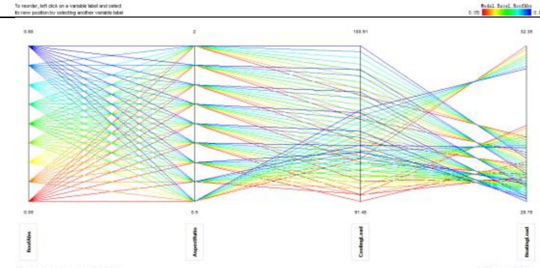
Philadelphia Climate Zone 4A

No. of Floors	Lines colored by Aspect Ratio Aspect Ratio Range [0.5-2]	Lines colored by Roof Absorptance Coefficient Roof Abs. Coefficient Range [0.05-0.88]
1		
2		
3		
4		
5		
6		

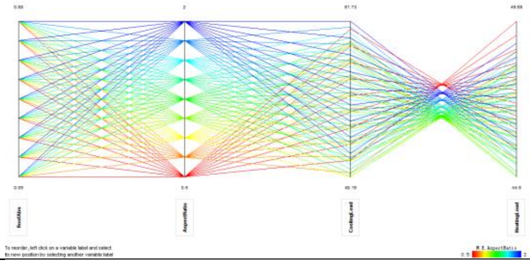
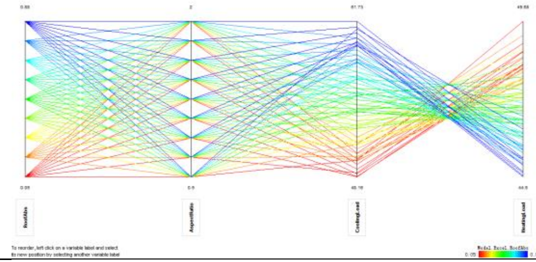
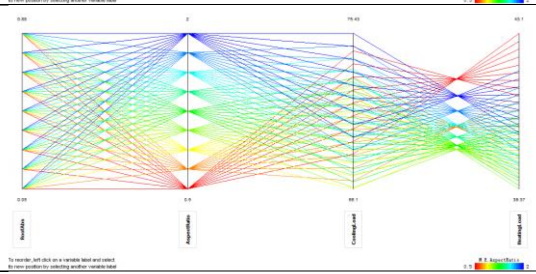
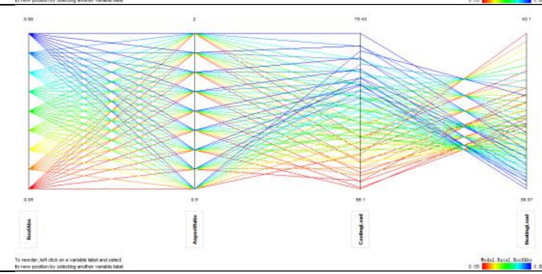
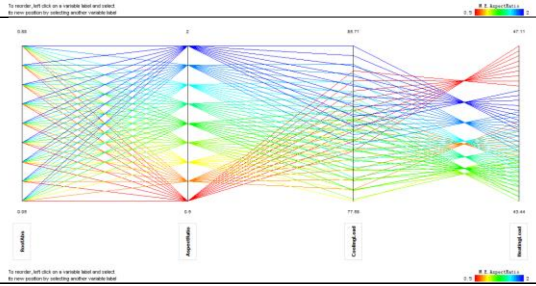
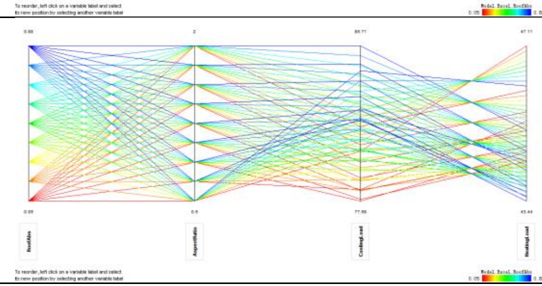
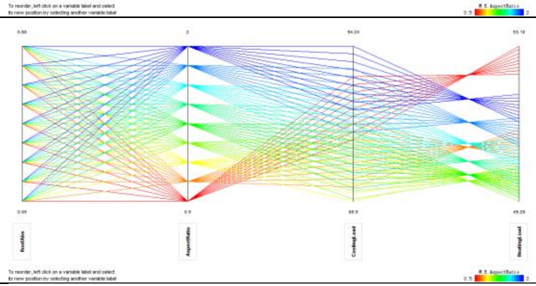
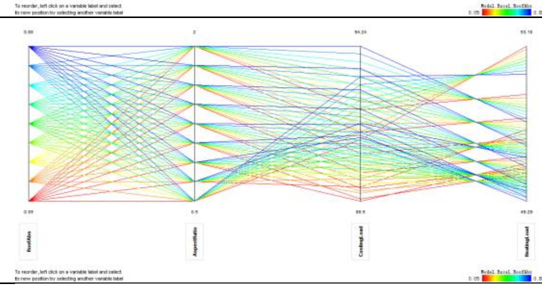
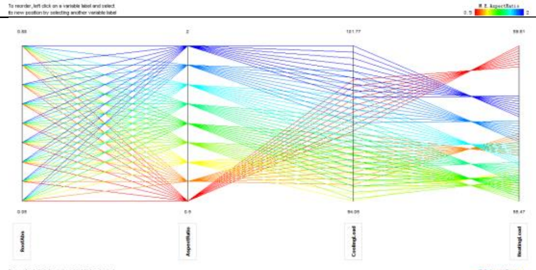
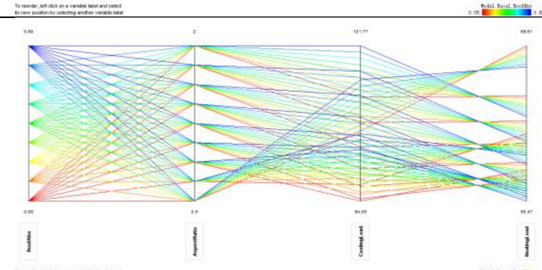
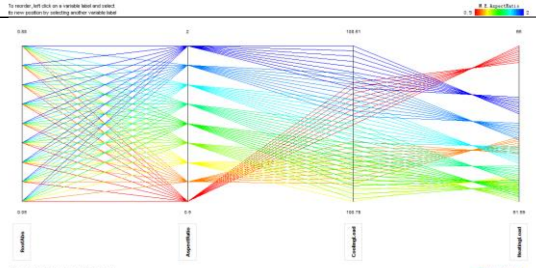
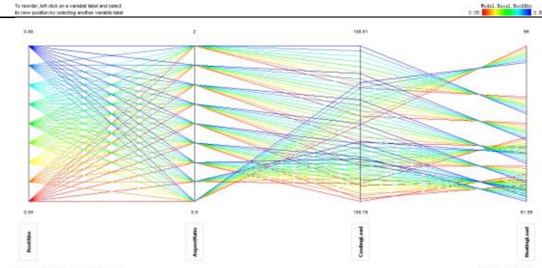
Seattle Climate Zone 4C

No. of Floors	Lines colored by Aspect Ratio Aspect Ratio Range [0.5-2]	Lines colored by Roof Absorptance Coefficient Roof Abs. Coefficient Range [0.05-0.88]
1		
2		
3		
4		
5		
6		

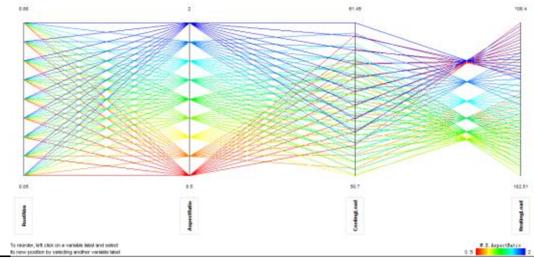
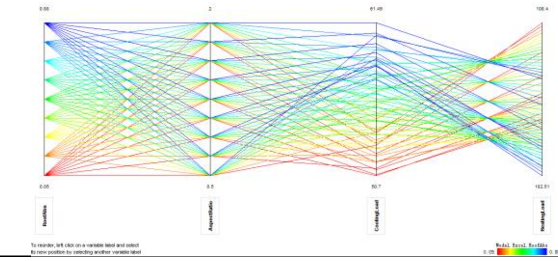
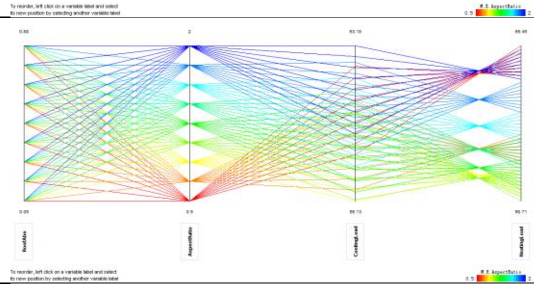
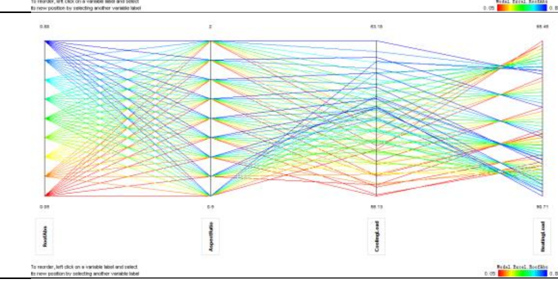
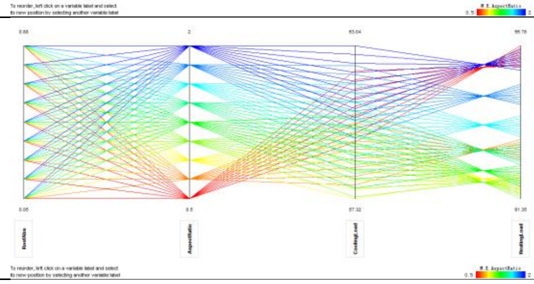
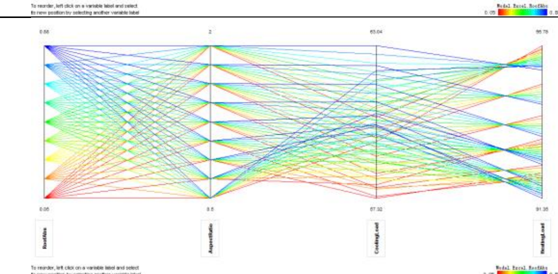
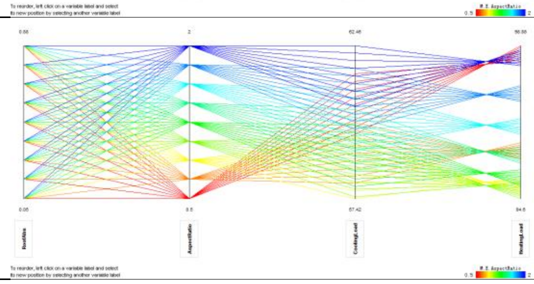
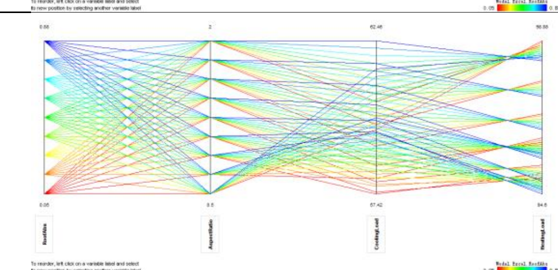
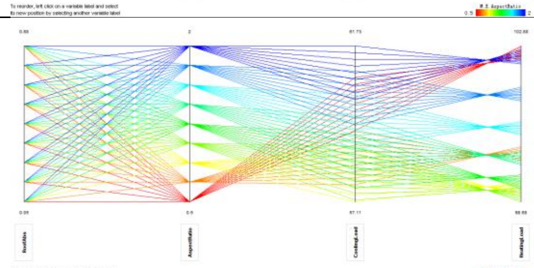
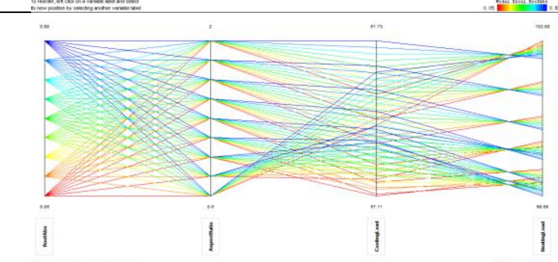
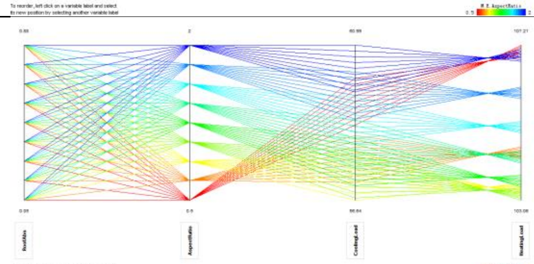
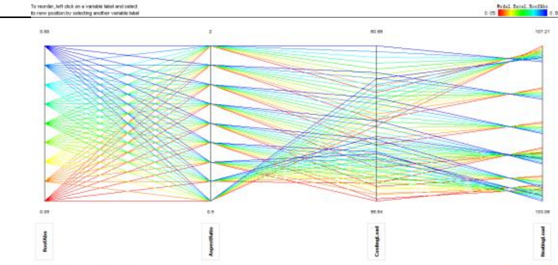
Denver Climate Zone 5B

No. of Floors	Lines colored by Aspect Ratio Aspect Ratio Range [0.5-2]	Lines colored by Roof Absorptance Coefficient Roof Abs. Coefficient Range [0.05-0.88]
1		
2		
3		
4		
5		
6		

Minneapolis Climate Zone 6A

No. of Floors	Lines colored by Aspect Ratio Aspect Ratio Range [0.5-2]	Lines colored by Roof Absorptance Coefficient Roof Abs. Coefficient Range [0.05-0.88]
1		
2		
3		
4		
5		
6		

Fairbanks Climate Zone 8

No. of Floors	Lines colored by Aspect Ratio Aspect Ratio Range [0.5-2]	Lines colored by Roof Absorptance Coefficient Roof Abs. Coefficient Range [0.05-0.88]
1		
2		
3		
4		
5		
6		

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